Roebuck Bay Invertebrate and bird Mapping 2006

Piersma, Theunis; Pearson, Grant B.; Hickey, Robert; Dittmann, Sabine; Rogers, Danny I.; Folmer, Eelke; Honkoop, Pieter; Drent, Jan; Goeij, Petra de; Marsh, Loisette

RESEARCH REPORT

*Roe*buck *B*ay *I*nvertebrate and bird *M*apping 20*06*

ROEBIM-06

by

Theunis Piersma
(Royal Netherlands Institute for Sea Research - NIOZ and Animal Ecology Group, University of Groningen, The Netherlands)

Grant B. Pearson
(Western Australian Department of Environment and Conservation - DEC)

Robert Hickey
(Central Washington University, Ellensburg, WA, USA)

Sabine Dittmann
(Flinders University, Adelaide, SA)

Danny I. Rogers
(Charles Sturt University, Albany, NSW)

Eelke Folmer
(Animal Ecology Group, University of Groningen)

Pieter Honkoop, Jan Drent & Petra de Goeij
(Royal Netherlands Institute for Sea Research – NIOZ)

Loisette Marsh
(Western Australian Museum)

This project has been funded by CALM Science Division, CALM Landscope Expeditions, CALM West Kimberley District, Central Washington University, Flinders University, Schure Beijerinck-Popping Fonds and the Netherlands Organization for Scientific Research (NWO).

This report was produced at the Broome Bird Observatory in late June/early July 2006

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1. Abstract

1. This is a report on a survey of the benthic ecology of the intertidal flats along the northern shores of Roebuck Bay in June 2006. In the period 11-20 June we mapped both the invertebrate macrobenthic animals (those retained by a 1 mm sieve) over the whole of the northern intertidal area of Roebuck Bay and the shorebirds that depend on this food resource. The northern mudflats previously had been benthically mapped in 1997, 2000 and 2002. In addition to the mapping efforts, as a reach-out to the Broome community, the project incorporated the 'Celebrate the Bay Forum' on 17 June on the CALM grounds in Broome. This one-day event was visited by about 150 people and was widely considered successful in generating enthusiasm for the ecology of the bay and concerns about its future well-being.
2. Our team comprised 38 participants with greatly varying levels of experience, but all with similarly high motivation and enthusiasm. We visited 532 sampling stations laid out in a grid with 200 m intersections. We made notes on the surface features of the mud, including the presence or absence of seagrasses. In the course of digging up, sieving and sorting the mudsamples from all the stations, we identified and measured more than 12,000 individual invertebrates. These animals represented 185 taxa at taxonomic levels ranging from species (bivalves, gastropods, brachiopods, some of the echinoderms and sipunculids), families (polychaete worms, crustaceans and sea anemones) to orders and phyla (Phoronida, Echiura, Nemertini and Tunicata).
3. Linear seagrass *Halodula uninervis* and oval seagrass *Halophila ovalis* were quite widespread again. They showed a level of recovery to the coverage earlier reported in June 1997, after their disappearance during the passage of cyclone Rosita in June 2002.
4. Of the 185 different taxa encountered in the mudcores, most had been found during earlier surveys. Nevertheless, about 26 taxa had apparently not been encountered before, including several small bivalves belonging to the Galeomnatidae. The relatively strong presence of the very small Galeomnatidae in the samples, and the relative abundance of minuscule transparent organisms such as skeleton shrimps Caprellidae retrieved, also compared with previous years, may indicate that the sorters, who routinely checked each other's trays at the end of each sorting, did a particularly thorough job. The 12,000 individual invertebrates found in the 532 samples is similar to the number retrieved from the 1000 sampling stations visited during the mapping of all intertidal flats in Roebuck Bay in June 2002.
5. At a considerable number of sampling stations across the intertidal flats we noted the presence of a new kind of large snail, the 'ornate' Ingrid-eating snail *Nassarius bicallosus*, occurring alongside the very similar scavenger *Nassarius dorsatus* in Roebuck Bay. Only a few individuals of *Nassarius bicallosus* had been found in Roebuck Bay before.
6. For all six suspension-feeding (*Siliqua* and *Anomalocardia*) and deposit-feeding (*Tellina*) bivalves, the distributions in 2006 were remarkably similar to those recorded in the surveys of 1997 and 2002. Given the stark and repeatable gradients in sediment type and tidal height this is perhaps not surprising, but given their wide distributions across these gradients and their variable recruitment patterns, perhaps it is.
7. Two 1-5 cm long species of tuskshell, or Scaphopoda, have previously been found on the intertidal flats of Roebuck Bay. The two species are pretty similar, but one has a smooth and the other a ribbed surface. In 2006 the smooth tuskshell *Laevidentalium* occurred widespread over all parts of the intertidal flats, living in very muddy as well as quite

sandy place, but the ribbed tuskshell *Dentalium* only occurred at the muddier sites in the Crab Creek corner and in the muds near Dampier Creek and the nearby mangal edge.

8. The long-armed brittle stars *Amphiura* sp. were among the most widespread species of the bay. Despite, or due to, their similarity, *Amphiura tenuis* and *Amphiura catephes* usually occurred together, *A. catephes* being the less numerous species, occurring much in the soft muddy areas of Crab Creek Corner where *Amphiura tenuis* did live.

9. All polychaete worm families were very widely distributed, occurring over much broader ranges of sediment types and tidal heights than the bivalve species. These widespread distributions could perhaps be explained as a result of the summation of much more limited species-specific distributions. ‘Pickled’ specimens were collected to make a start with polychaete species assignments.

10. During the previous surveys Tunicates were always at a few places in the intertidal, but in June 2006 they occurred in remarkable densities over remarkable extends of intertidal habitat along the northern shores. Probably four species were common: two or three solitary living species that were buried close to the sediment surface, sometimes occurring in carpet-like densities and always occurring in colonies, and a rooted, colonial, form that also occurred in colonies but not over the same extent as the solitary species.

11. Grey-tailed Tattlers were widespread on the western flats of the bay, just as during previous surveys. In contrast, the feeding distribution of Great Knots and Red Knots which feed on bivalves and show a preference for feeding sites near the sea-edge has varied over the years. In mid June 2006, Great Knots were found over a wide area of mudflats, albeit with the highest concentrations occurring in the east of the bay. In contrast, we could only find a single feeding concentration of Red Knots – in the far east of the bay, just south of Crab Creek. This distribution of Red Knots came as a surprise to us, as the species tends to prefer slightly sandier sediments than Great Knot, e.g. the Dampier Flats. Indeed, we found rather few shorebirds on these western flats. It is possible that the cause of the discrepancy lies on high tide roosts rather than on the intertidal flats. The closest available roost sites to the Dampier Flats, Quarry Beach and Simpson’s Beach, are both heavily disturbed in the dry season. For shorebirds that cannot tolerate the disturbance levels at these roost sites and therefore roost elsewhere, the costs of commuting to the Dampier Flats to feed may be too high.

12. A biodiversity hot spot analysis revealed that overall macrozoobenthic invertebrate diversity was highest in parts of the Dampier Flats and in the narrow intertidal zone just south of the Broome Bird Observatory. Overall biodiversity was negatively correlated with penetrability, a measure of the silt content of the sediments. However, when bivalves alone were considered, biodiversity peaked in areas adjacent to where overall biodiversity was highest and the relationship with siltiness was reversed: the highest diversity of bivalves was found in the muddiest parts of the intertidal flats of Roebuck Bay.

2. Introduction

Roebuck Bay is world-renowned as a non-breeding site for migratory shorebirds. These small to medium-sized birds – sandpipers, plovers, curlews and the like – nest in the far northern hemisphere, in habitats ranging from Mongolian steppes to high arctic tundra. In the non-breeding season they inhabit a very different world, depending on intertidal flats where they feed on benthic animals. The rich and diverse benthos of Roebuck Bay supports a very large and diverse shorebird population. In the east-Asian – Australasian flyway, Eighty-mile Beach is the only site that supports a larger number of shorebirds, while the diversity of species occurring in internationally significant numbers in Roebuck Bay is unparalleled. About 150,000 roosting shorebirds use the place. Indeed, there are few places on earth where soft bottom intertidal mudflats support larger numbers of migratory shorebirds. Roebuck Bay is one of less than only twenty comparable coastal areas scattered around the globe. The features that characterise this Bay and make it so outstanding are varied and complex (Rogers *et al.* 2003). They have also been the subject of considerable scientific and community investigation over the past 10 years. This unusual collaboration between science and community has been the catalyst for another effort to try and map the nature and distribution of the sediments of Roebuck Bay, the one in 2006 being the fourth in a row, this one with a focus on the northern shores.

This information is essential if we are to conserve the immense and internationally shared natural values of these important shorebird sites, and to find informed compromises between the increasing use of the foreshore by the ever increasing human population in the Kimberley Region and their use by the beasts and the birds. A considerable proportion of the world's Great Knots (*Calidris tenuirostris*) depends on (very specific portions of) Roebuck Bay for moult, survival and fuelling for migration. This is also true for perhaps all the Red Knots (*Calidris canutus piersmai*) and Bar-tailed Godwits (*Limosa lapponica menzbieri*) of specific, reproductively isolated and morphologically and behaviourally distinct subspecies. The intertidal macrobenthic community of places like Roebuck Bay contains a unique assemblage of species. Some of these species will be new to science.

The 2006 project builds on the logistical methods and the techniques developed and used so successfully during the co-operative intertidal benthic invertebrate mapping project in Roebuck Bay in June 1997 (ROEBIM-97; Pepping *et al*. 1999), the benthic invertebrate mapping effort along the Eighty-mile Beach foreshore in October 1999 (ANNABIM-99; Piersma *et al.* 2005), the benthic invertebrate mapping across the whole of the Roebuck Bay intertidal in June 2002 (SROEBIM-02; Piersma *et al*. 2002) and the low tide shorebird counting methods developed by Danny Rogers in Roebuck Bay from October 1997 onward. In the period 11-20 June 2006 we mapped both the invertebrate macrobenthic animals (those retained by a 1 mm sieve) over the whole of the northern intertidal area of Roebuck Bay (Fig. 1) and the shorebirds that depend on this food resource. We focused on the northern mudflats; mudflats that had been benthically mapped in 1997, 2000 (during the bird expedition Tracking-2000) and again in 2002. In addition to the mapping efforts, as a reach-out to the Broome community the project incorporated the ‘Celebrate the Bay Forum’ on 17 June on the CALM grounds in Broome. This one-day event was visited by about 150 people and was widely considered successful in generating enthusiasm for the ecology of the bay and concerns about its future well-being.

Our team comprised 38 participants (2 Landscope Expeditioners, 11 local volunteers, 13 logistical support, 13 Science support). There were 10 scientific co-ordinators (Theunis Piersma, Petra de Goeij, Pieter Honkoop and Jan Drent from NIOZ, Eelke Folmer from the University of Groningen, Grant Pearson from CALM, Bob Hickey from Central Washington University, Loisette Marsh from the Western Australia Museum and Danny Rogers from Charles Sturt University). We visited 532 sample stations laid out in a grid with 200 m intersections, mostly also covered in 1997, 2000 and 2002. In the course of digging up, sieving and sorting the mudsamples from all the stations, we identified and measured more than 12,000 individual invertebrates. These animals represented 185 taxa at taxonomic levels ranging from species (bivalves, gastropods, brachiopods, some of the echinoderms and sipunculids), families (polychaete worms, crustaceans and sea anemones) to orders and phyla (Phoronida, Echiura, Nemertini and Tunicata).

In this report we aim to summarise the methods and the results based on preliminary analyses carried out at Broome Bird Observatory during and after the expedition in late June 2006. It also enables us to thank the many individuals who put in so much of their expertise, time and working power.

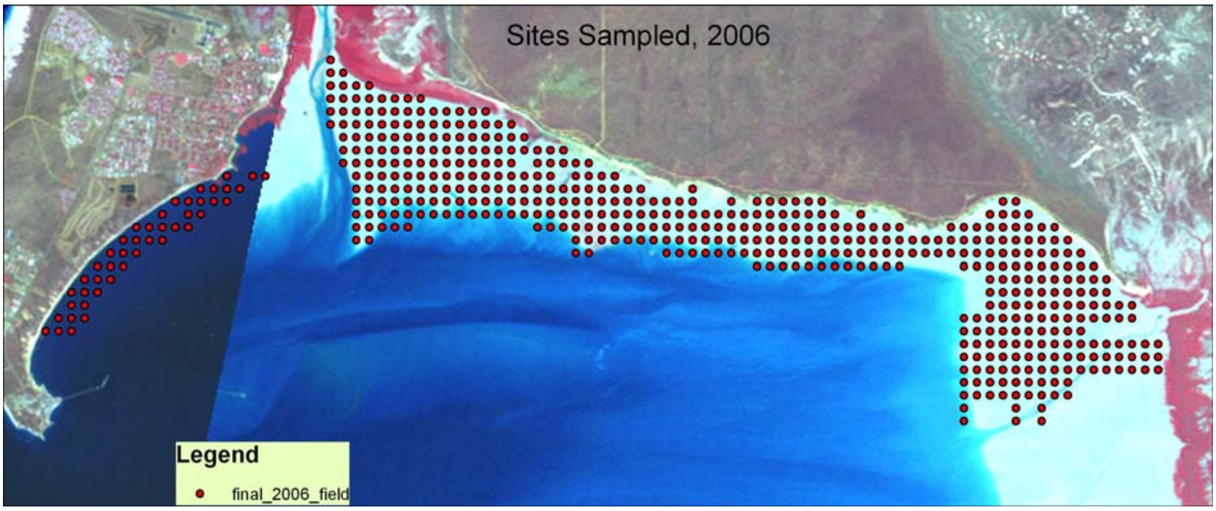


Fig. 1. Stations (200 m grid intersections) from which samples of sediments and the macrozoobenthic community (i.e. animals retained on a 1 mm mesh) were actually obtained in June 2006. Gaps in coverage either refer to unvisited places, rocky outcrops that made sampling impossible or, in 1-2 cases, lost samples.

2. Methods

General and benthos

The study took place at Roebuck Bay between Crab Creek in the northeast and Town Beach in the northwest (Fig. 1). With a neap tide on 23 June, sampling during the first week took place with tidal ranges that did not expose the full extent of the intertidal flats. For most of the project, the range (or distance from the shore) of our sampling was constrained by these neap tides.

Sampling stations were placed on a 200 m grid. We tried to cover as much as possible of the areas sampled not only in June 1997 and then revisited in March-April 2000 (during the *Tracking-2000* expedition, also based at the Broome Bird Observatory) and June 2002. Every sampling station received a unique station number composed of a row number (from south to north), a column number (from west to east) and an indicator of north (n) or south (s), and example being “r14c56n” (Fig. 2). Each station number combined with predetermined co-ordinates on a UTM-projection, using the Australian Map Grid 1966 as the horizontal datum. Navigating to the stations by GPS, teams of 2-4 people visited each of the stations based upon the geographical co-ordinates that were pre-assigned to them. Most samples were taken by teams on foot, but the whole area east of the BBO, the deep muddy areas around Crab Creek, were all visited by the two hovercraft teams.

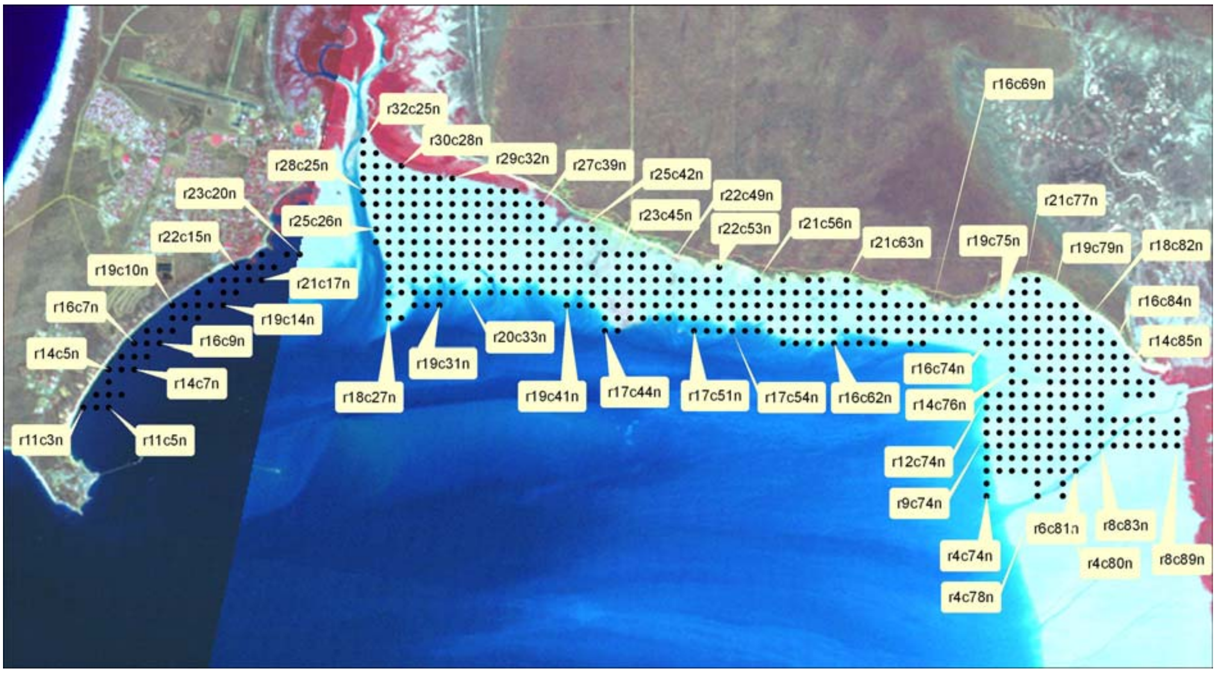


Fig. 2. The naming in rows (r) and columns (c) of all the grid-points/sampling stations successfully examined in June 2006.

At each station 3 corers made of PVC-pipe were pushed down to a depth of 20 cm (less if the corer hit a hard shell layer below which we expect no benthic animals to live), and the core samples, each covering 1/120 m², removed (Photo 1). The samples with a total surface area of 1/40 m² were sieved over a 1 mm mesh and the remains retained on the sieve placed into a plastic bag, to which a waterproof label indicating the station was added. At the same time a sediment sample was taken with a depth of 3-5 cm and a diameter of 4.4 cm (surface area = 1/650 m²), stored in a labelled plastic bag and kept at outside temperature for transport to the laboratory. These sediment samples will be analysed either in a laboratory in Perth or at NIOZ, Texel.

In the field, records were made of the nature of the sediment (varying from mud to coarse sand) by way of penetrability (depth of footsteps made by a person, in cm), and the presence of visible larger and therefore more uncommon animals on the mud surface, the sort of animals (sentinel crabs, anemones, Ingrid-eating snails *Nassarius* sp.) that may be missed by our sampling technique (but see below). The sheets also allowed us to record which of the predetermined stations were actually visited, the names of the observers and the times of sampling.

The 'biological samples' were taken back to the Broome Bird Observatory and immediately sorted in low plastic trays in the sorting area just outside the Pearson Laboratory (Photo 2) or stored in a fridge at 4°C for a maximum of 1.5 days, and then sorted. All living animals were then kept in seawater, again at 4°C for a maximum of one day, upon which they were examined under a microscope by specialists seated indoors in the BBO-mudlab (Photo 3). All invertebrates were assigned to a single taxonomic category (see Table 1). At the same time the maximum length (in case of molluscs and worm-like organisms), or the width of the core body (in brittle stars), was measured in mm. The latter information will be of use in making predictions of the benthic biomass values using existing predictive equations.

We also upgraded the historical reference collection for more detailed study of the species at a later stage. Some of the polychaetes collected were preserved for later detailed examination by S. Dittmann. Most bivalves were dissected by J. Drent and the flesh dried and incinerated for determination of biomass values. We added to the ethanol-collection of bivalve tissues to be used for genetic screening of species differences (T. Compton, P.C. Luttikhuizen *et al*.).

Photos 1. (Top) Lucie Southern, a CALM volunteer from England (left) and Bryan Webster from Broome (right) at a sampling station off Quarry Beach; they are about to take their samples. (Bottom) Old-hand Jack Robinson from Sydney putting a sample in the sieve held by Bob Hickey. Photos by Theunis Piersma and Jan Drent.

Photo 2. The sorting process just outside the BBO-mudlab in full swing. Photo by Jan Drent.

Photo 3. Sabine Dittmann, Loisette Marsh and Danny Rogers (from left to right) going through the identification of sorted samples in the BBO-mudlab. Photo by Theunis Piersma.

Shorebirds

The present survey took place in June, in the Australian dry season. This period corresponds with the boreal winter, and is therefore the time of year at which adult migratory shorebirds are on the breeding grounds, many thousands of kilometres from their non-breeding areas in Roebuck Bay. Nevertheless, reasonably good numbers of shorebirds were present. This was because many species of migratory shorebird in Australia take several years to reach maturity.

Until they do so they remain in Australia, not migrating north. In all, in mid June 2006 we counted 5612 shorebirds on the high-tide roosts along the northern beaches of Roebuck Bay. This number was much lower than the 40-45,000 that would be expected in the summer months (*c*. October-March), but was typical for a June count.

Shorebird distribution at low tide on the mudflats of Roebuck Bay has been mapped several times in the past 10 years. We counted the shorebirds in cells measuring 200 by 200 m, each with a benthos sampling point in the middle. Observations were made with the help of telescope and binoculars (bird surveys do not require any of that tedious benthos-sorting process!). The shorebird mapping methodology, developed specifically for the bay, is described in more detail in previous expedition reports.

Mapping

Once more, maps were to become the foundation upon which a benthic sampling expedition was based. Fortunately, the ROEBIM-97 and Tracking 2000 databases were available. The primary base maps were 1994 (low tide) and 1995 (high tide) Landsat images, sample points from ROEBIM 97 and Tracking 2000, and two point grids for sampling in 2002. These two point grids included a 200 m grid for the northern shore and a 400m grid for the eastern and southern shores. These were generated using a custom Visual Basic program and included AMG zone 51 (Ausgeoid 66 datum) co-ordinates and a unique identifier. Custom maps were generated for every field mapping team (see Fig. 3 for an example). They included a set of points (and co-ordinates) on a Landsat image base.

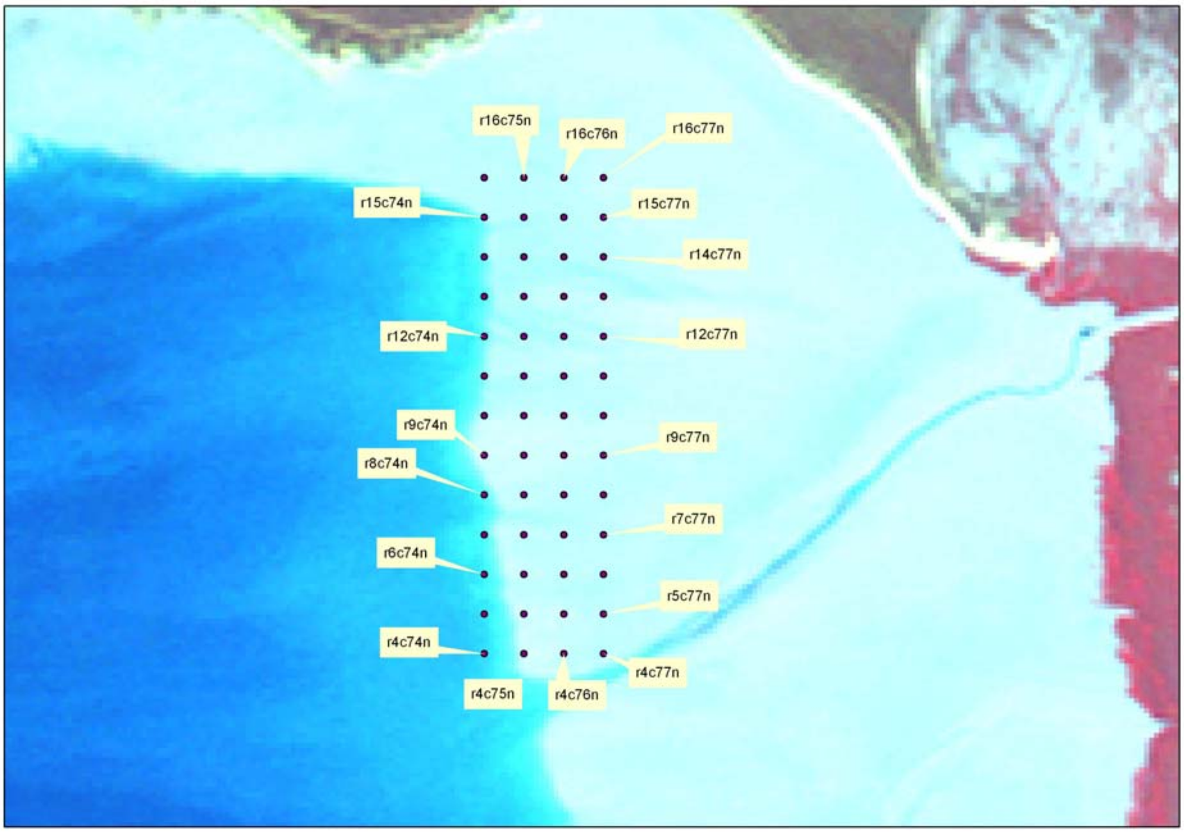


Fig. 3. Example of the field map with 'hopeful' sampling stations for the hovercraft team of Glyn Hughes on 13 June 2006, such as they were routinely prepared by Bob Hickey. Naming in rows (r) and columns (c).

Sample points were located in the field using one of twelve handheld GPS receivers of five different models. They were invaluable for finding sample sites on the otherwise nearly featureless mudflats. For those that were keen, sample points were entered as waypoints into GPS receivers – thereby making the finding of those points even simpler. We also discovered that GPS use was far simpler now that Selective Availability has been turned off. Daily progress maps showing sites sampled to date were generated daily and used during evening briefings.

Once the field sampling was complete, all field, bird, and species data were entered into the GIS database – often requiring considerable gyrations to get everything in the proper format. The results were the maps shown in this report. These are preliminary maps – the data are about 98% complete. The lines on the black-and-white maps represent the spring high and low water lines.

A new feature of the present report is the comparison that could be made with the results of previous surveys: those in June 1997 and June 2002. The extent of the surveys along the northern shores during these two previous surveys in comparison with the mapping efforts in 2006 are shown in Fig. 4. The data collected in March 2000, although available in the database, for reasons of space were not incorporated in the comparisons reported below.

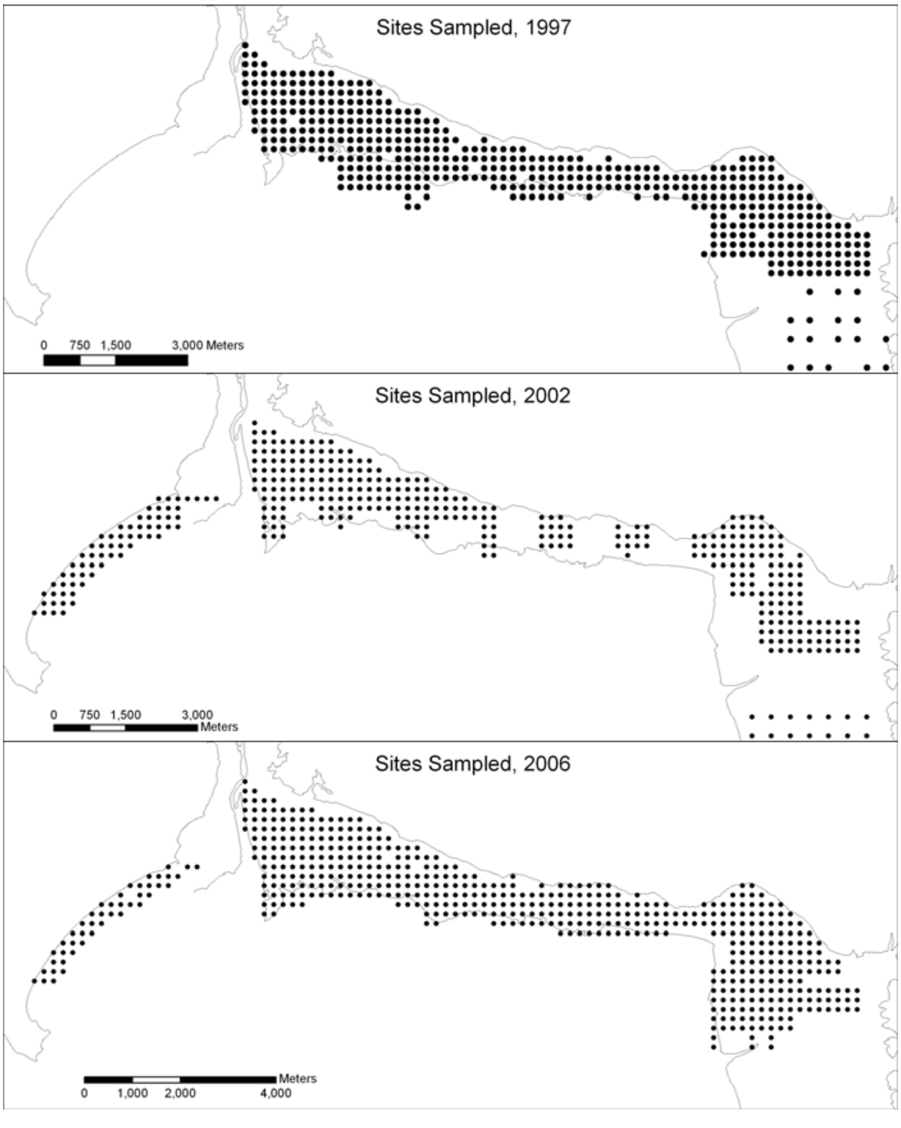


Fig. 4. The extent of the grids along the northern shore sampled in 1997, 2002 and 2006. In 1997 we did not cover Town Beach in the west, and in 2002 sampling along the northern shores was limited to the bird mapping areas also covered in March 2000.

4. Results and discussions

What's the mud like? Mapping how deep people sink!

In sedimentary environments such as most ocean and sea floors, and such as the sand- and mudflats of the Roebuck Bay intertidal, the sediment characteristics are a defining part of life. To a buried bivalve, a seastar or a sipunculid it matters a great deal whether it finds itself on, and in, relatively coarse sands or whether it sits in really fine-grained mud. Sediment characteristics also matter to the people doing benthic mapping. Most sands provide stable hard substrates to walk on; mapping is like a stroll on a sandy beach, really pleasant because one hardly sinks in. Life as a mapper can be quite different in fine-grained soft muds, especially in conditions when one sinks deeper than the knees. Locomotion becomes very tedious, or for some people, utterly impossible. In spite of the stress on such mud, it can also be fun. Deep mud has triggered mud-wrestling of a kind on more than one occasion (Photos 6)!

As during some of the previous surveys we routinely recorded the depth of the footsteps on the sands and muds on the field sheets, calling the measure 'penetrability' (Photo 4). Figure 5 shows how penetrability values are distributed over the northern shores. The deep inshore mud between the BBO foreshore and Crab Creek stands out (Photo 5; this was the area sampled by small hovercraft!), as do the nearshore patches of mud along the northern foreshore (especially near the mangroves along Dampier Flats) where a person sank to depths of up to 10-15 cm, still not quite ankle-deep. Town Beach, and actually most of the northern foreshore, is rather hard and sandy. Based on what we know about grain size distributions from previous years (Pepping *et al.* 1999; T. Compton pers. comm.), penetrability actually seems a fair predictor of grain size, and also gives consistent estimates between years (the correlation coefficient between records in 2002 and 2006 is about 0.5). In the General Discussion we shall see that penetrability values are correlated with invertebrate species numbers and other benthic biodiversity estimates.

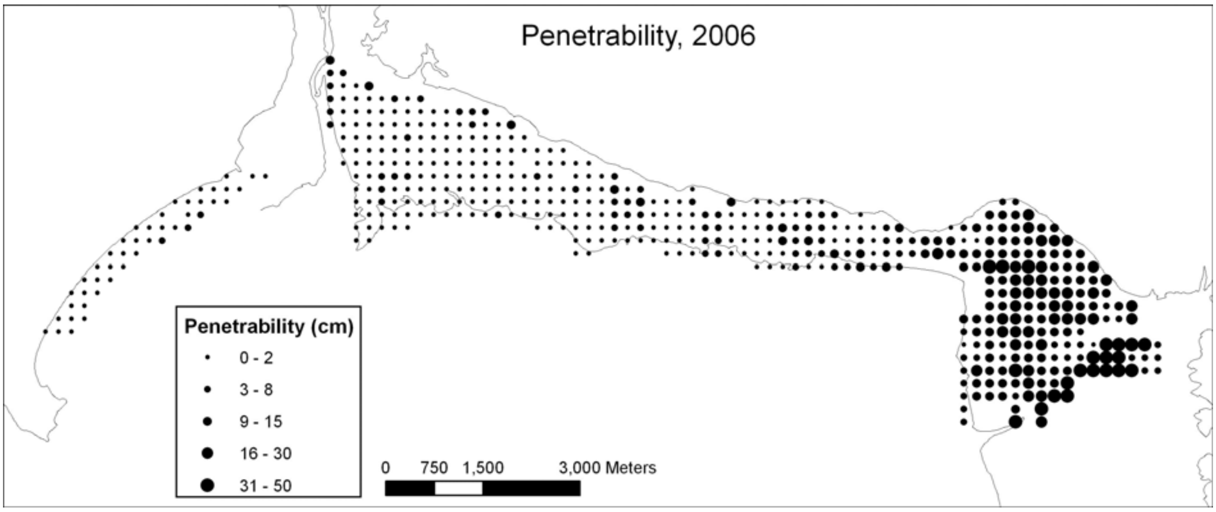


Fig. 5. Depths to which participants of ROEBIM-06 sank in the mud in June 2006 (denoted with the term 'penetrability') on the northern intertidal areas of Roebuck Bay.

Photo 4. Taking cores just east of Fall Point in a muddy area with penetrability values of 3-8 cm. Note that sediments get even softer closer to the low water mark. Photo by Stephanie Gadal.

Photo 5. Crab Creek corner, the area bordered by Crab Creek in the background and Little Crab Creek in the fore-ground, the place with the highest penetrabilities and the deepest grey-blue mud of the bay. Remarkably, within this area of soft muds an area of coarser sands has established itself over the past 10 years; visible here as the brownish structure in the middle of the picture. Photo taken from helicopter in mid June 2006 by Doug Watkins.

Photos 6. The return of the troops at BBO after sampling at One Tree, in the deep blue muds near Crab Creek. Photos by Theunis Piersma.

Mapping organisms on the surface: what do we actually measure?

On the field-sheets we recorded time of sampling per station, the penetrability of the mud by an average person (see above) and also made notes on the presence of linear seagrass and oval seagrass and on the surface-appearance of different animals. Data on penetrability are easy to record and seem very consistent. Seagrass always occurs on the surface of the sand and muds, and once an observer is used to recognising it, it is difficult to confuse or miss.

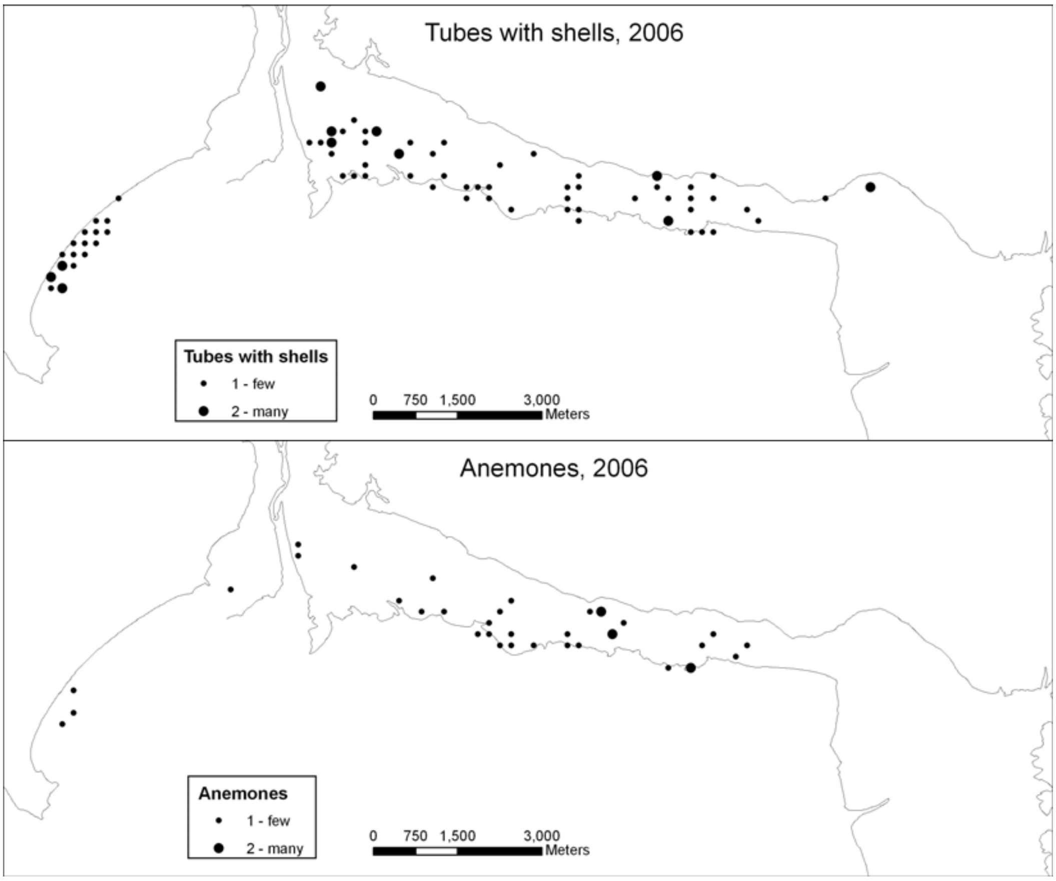


Fig. 6. Examples of data on the scarcer surface features recorded on the field sheets, in this case that of tubes with shells (often attributable to the polychaete family Onuphidae) (top) and that of anemones (bottom). Both of them only occur, or were only recorded (see below), on the sandy areas west of BBO.

The same cannot be said for the animals on the surface. Some may be too scarce to be noticed by inexperienced or tired observers (tubeworms with shells and the smaller anemones, for example; see Fig. 6), whereas others show so much variation with respect to whether or not they show up on the surface, that sometimes they may be seen and sometimes they may not be. As a case in point, we noticed on 26 June 2006 on the Dampier Flats that whilst no starfish *Astropecten* sp. were seen at all during the mid afternoon (at about midtide), they appeared from the sand around 17 hr and were fully emerged when light levels really began to fall around 17:30 hr. Similarly, pebblecrabs *Leucosia* sp. began to show up on the surface in considerable numbers from 17 hr onwards. If there is a strong effect of light levels on surface presence and visibility in some species, we expect a strong time-effect on positive records. In addition to time effects, there may also be effects of sediment type and of course there may be interactions between sediment type and time of tide or day on whether or not invertebrates are seen on the surface.

The most striking example that such effects may be real comes from a comparison between the surface records of large Ingrid-eating snails *Nassarius dorsatus* (Photo 7) and the densities recorded on the basis of sieved cores (making the probably robust assumption that with the latter method there is no escape from detection). On the basis of the field-records (Fig. 7 top) we would state that large ‘Ingrids’ occur widespread and abundant on the western parts of the northern shore, but that they are much scarcer east of BBO, in the deep mud near Crab Creek. However, when we look at the map generated on the basis of the sediment cores (Fig. 7 bottom), the picture is almost reversed, with good densities recorded in the muds near Crab Creek and along Dampier Creek as well, and not much elsewhere! In this case we must conclude that on the sands the Ingrid-eating snails are much more surface-active and/or visible than in the soft muds, despite occurring in larger densities in the latter intertidal habitat.

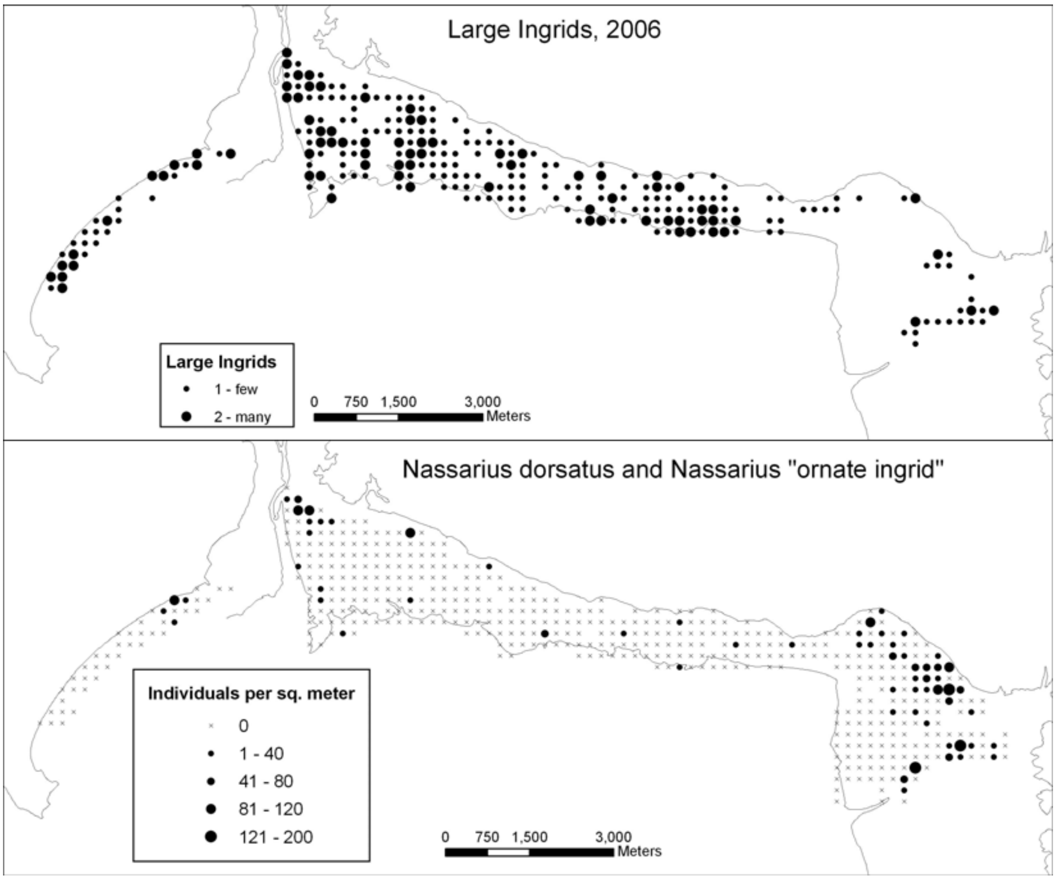


Fig. 7. ‘Distributions’ of large Ingrid-eating snails *Nassarius dorsatus* (and *bicallosus*; also known as the ‘ornate Ingrid’ these days) as apparent from the records in the field-sheets (visible, surface presence) (top) and in the mudcores (bottom).

Similar to the scavenging snails *Nassarius*, surface present sentinel crabs *Macrophthalmus* sp. seemed to be particularly thin on the ground near Crab Creek (Fig. 8 top) but according to the mudcores actually occurred very widespread throughout the intertidal sampled in June 2006 (Fig. 8 bottom). Figure 8 (top) therefore reflects the presence of surface-active *Macrophthalmus* and/or astute field observers more than it does the distribution of these crabs!

Photo 7. An Ingrid-eating snail *Nassarius dorsatus* crawling along the surface of Dampier Flats. Cueing in on smell in the surface water layer, it apparently is uninterested in the egg-string that crossed its path, carrying it along as it moves on. Photo by Nicholas Branson.

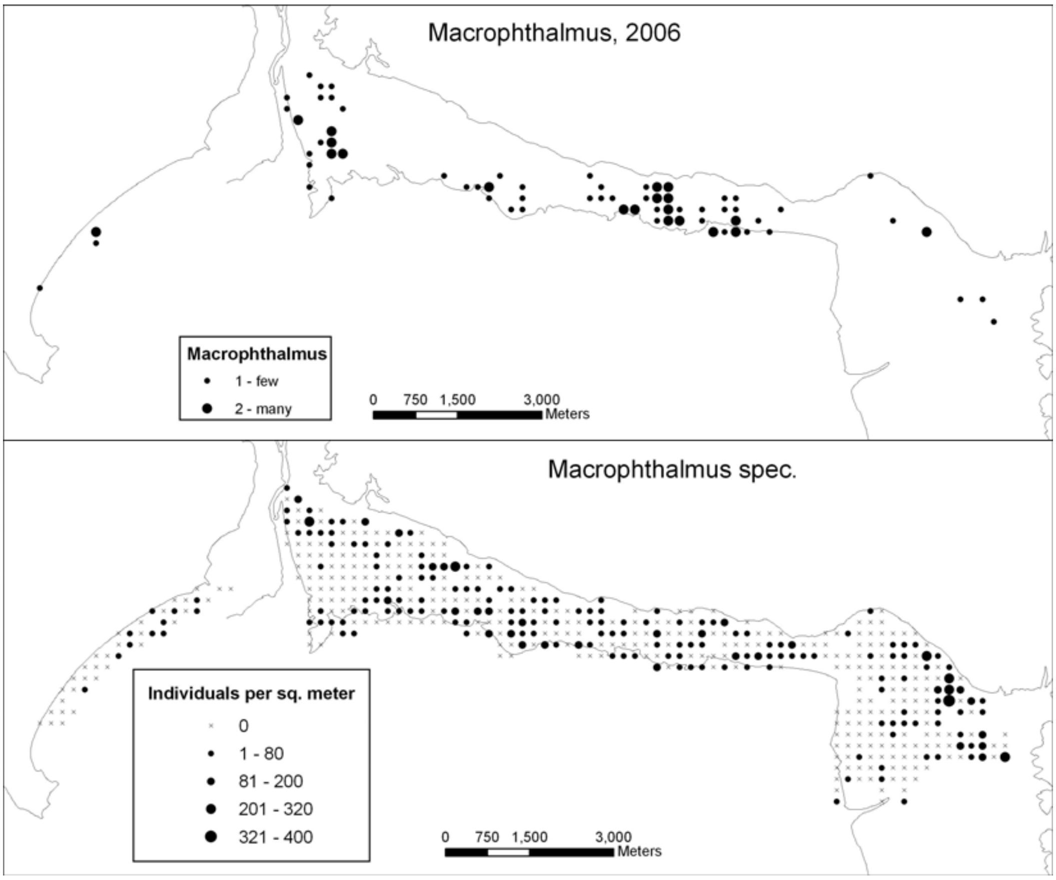


Fig. 8. Distributions of sentinel crabs *Macrophthalmus* sp. as apparent from the records in the field-sheets (visible, surface presence) (top) and in the mudcores (bottom).

A very striking example of surface-dwelling animals on the intertidal flats of Roebuck Bay are the green worms (Photo 8), worms belonging to the polychaete family Phyllodocidae. These worms are probably predators, and like all invertebrates exposing themselves before the very eyes of surface-predators like shorebirds, they must be inedible. In the case of Ingrid-eating snails the inedibility probably stems from having a tough, heavy shell (and a tough constitution that enables them to eat themselves out of most gizzards they end-up in?). In the case of seacucumbers it may be their habit of throwing out their sticky guts when attacked, the sticky substance incapacitating the attacker. The solitary - but carpet forming - Tunicates that were so abundant in 2006 (see below) may be just as unprofitable as food as the sediments they live in; they consist mostly of sand. In the case of the green worms it is probably a poison that prevents them from being eaten by shorebirds and crabs. When you are poisonous and need to be on the surface, advertising this trait helps. This would explain why green worms are a shiny green. Nevertheless, green worms sometimes hide in the sediment or in the reef (H. Macarthur pers. comm.). Although the core sampling shows that they occur in low numbers across the northern intertidal (Fig. 9 bottom), they were only found consistently and in large densities on the surface off Wader Beach, just west of BBO (Fig. 9 top; sampled late afternoons).

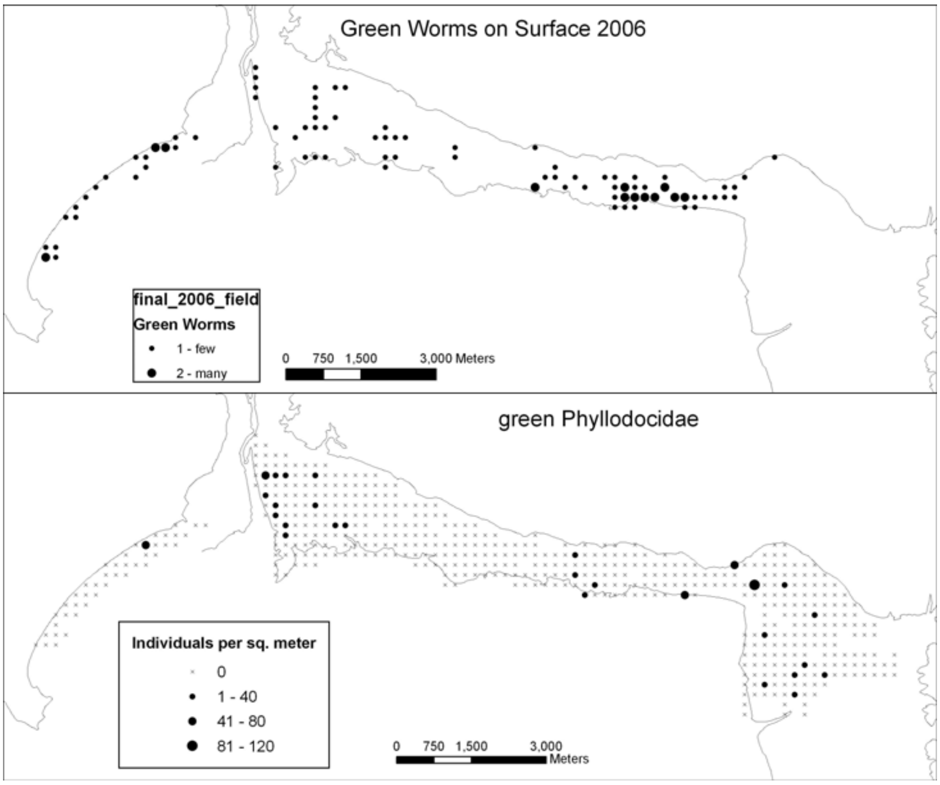


Fig. 9. Distributions of green worms on surface, also known as green Phyllodocidae, as apparent from the records in the field-sheets (visible, surface presence) (top) and in the mudcores (bottom).

Photo 8. A surface-dwelling green worm Phyllodocidae that probably is poisonous. Photo by Jan Drent.

The goings and comings of seagrasses on the northern foreshore

Seagrasses represent one of the rare higher plants that are truly marine. Seagrasses may cover much of shallow nearshore water areas and intertidal flats but are quite susceptible to disturbances. Mechanical reworking of sediments usually herald the end of good seagrass coverage, and in tropical areas the passage of cyclones with the concomitant forceful stirring of water and sediments may not be a good thing. We believe that our data on the changing cover of seagrasses on the northern shores of Roebuck Bay provide a good example of what happens after a cyclone event, in this particular case cyclone Rosita the eye of which passed just west of the bay in the morning of 20 April 2000 (destroying the EcoBeach tourist report in the process).

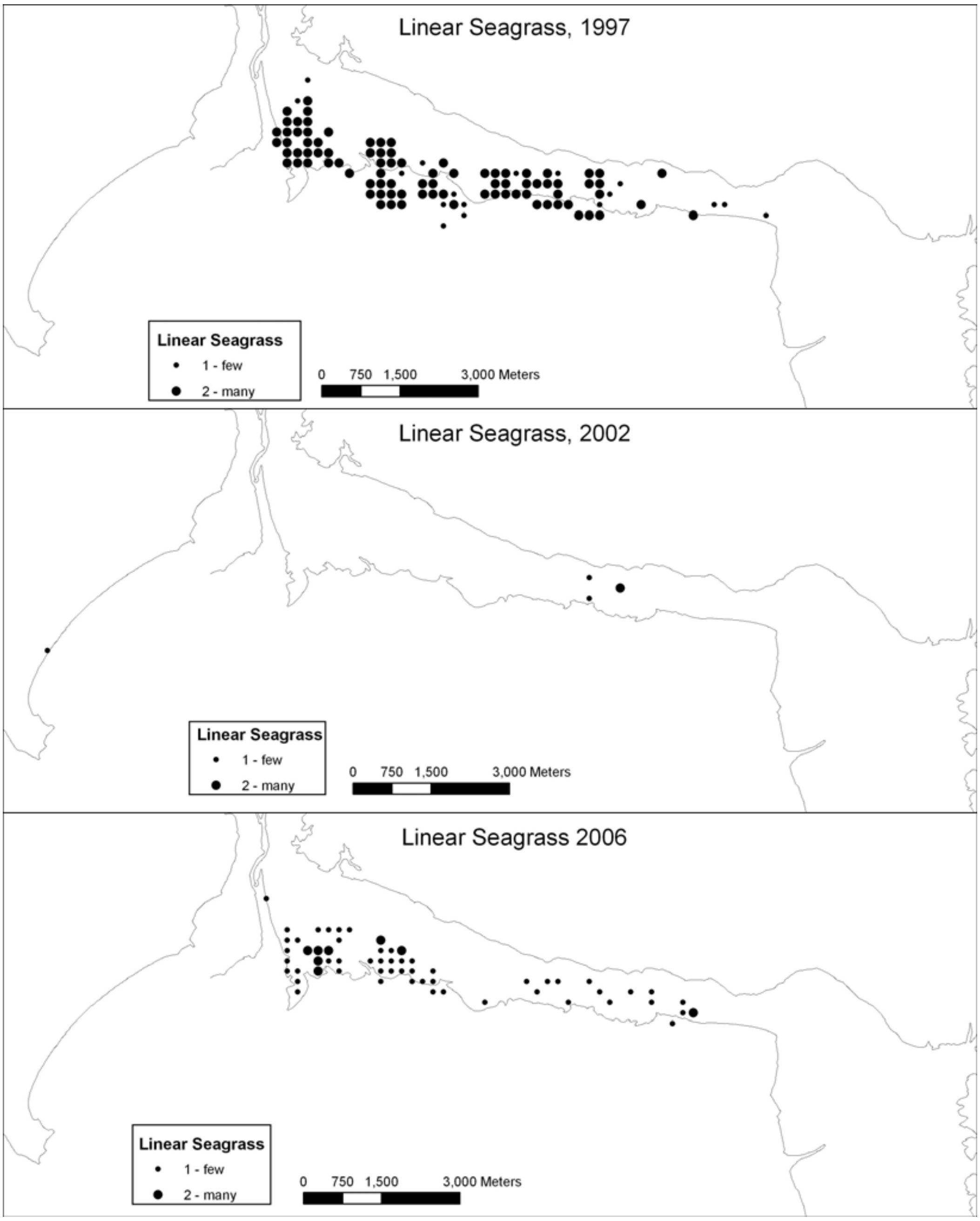


Fig. 10. Extent to which linear seagrass *Halodula uninervis* was encountered on the northern shores of Roebuck Bay in June 1997, June 2002 and June 2006.

Linear seagrass *Halodula uninervis* and oval seagrass *Halophila ovalis* were abundant over large extents of the lower northern shores in June 1997 (Figs. 10 and 11, top panels), and were still common during the benthic surveys that we carried out in March 2000 (not shown). Two years after the passage of cyclone Rosita, in June 2002, linear seagrass was encountered at only three sampling stations (1%; Table 1) halfway the northern beaches (Fig. 10) and oval seagrass at only 4 sampling stations (Fig. 11). Another four years later, in June 2006, especially the oval seagrass had made a spectacular come back, although the distribution by now has shifted slightly westward (Fig. 11). Recovery of linear seagrass (Fig. 10) has been somewhat slower, confirming a well-known difference in the potential for recolonisation between the two seagrass species.

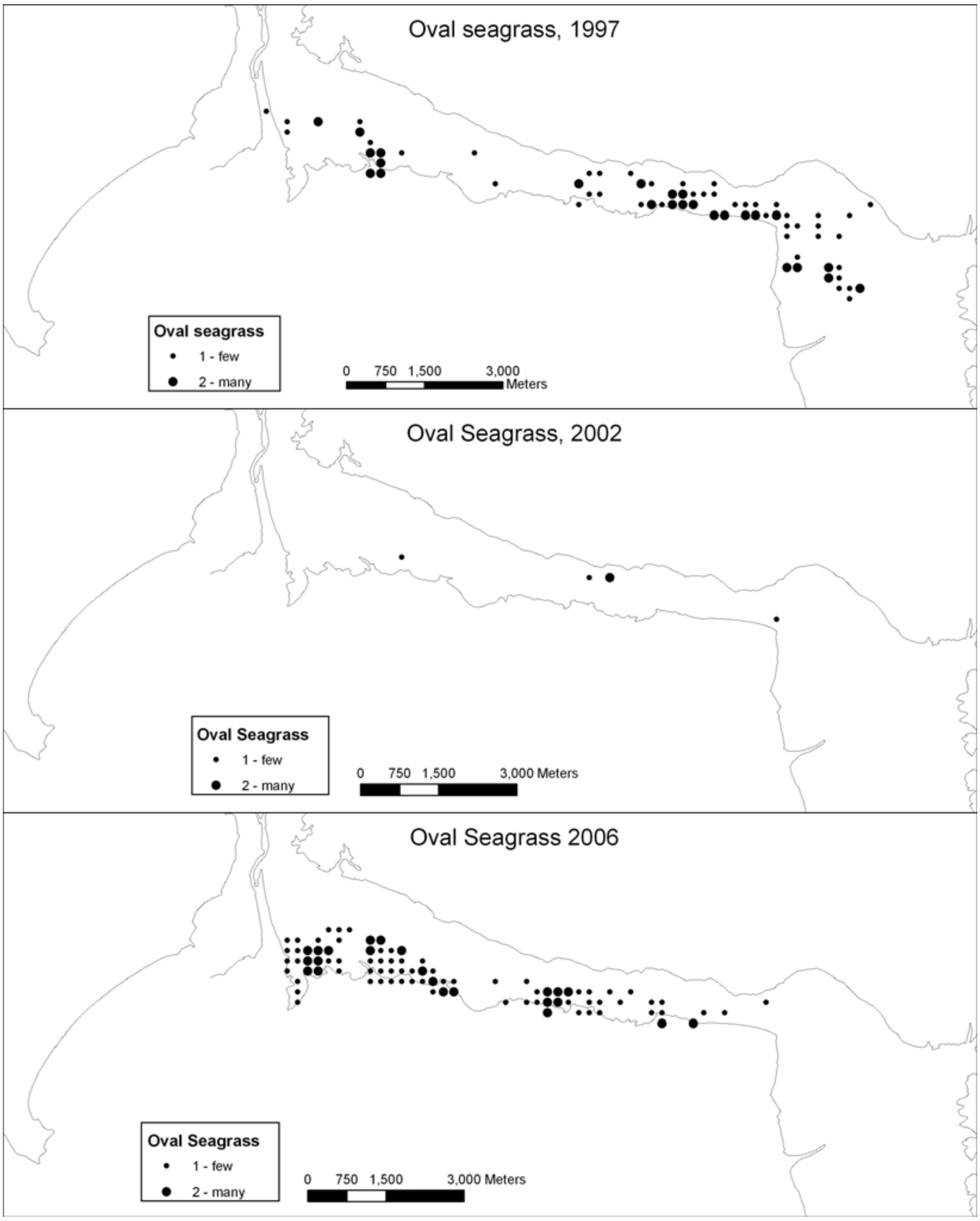


Fig. 11. Extent to which oval seagrass *Halophila ovalis* was encountered on the northern shores of Roebuck Bay in June 1997, June 2002 and June 2006.

In terms of overall coverage, the recovery of oval seagrass with respect to the situation in 1997 has been complete (Table 1). It is interesting that coverage values do not change much if we select for sampling stations that have been visited in all three years. For linear seagrass recovery values are quite a bit lower when considering all sampling stations (a 50% recovery between 2002 and 2006 with respect to 1997; Table 1), but the estimate is actually 75% if we count only revisited sites.

We know that cyclones may not be the whole story. In the mid 1970s Bob Prince (pers. comm.) documented extensive seagrass cover on the lower parts of Town Beach, including the finding of feeding trails by dugong (see photo on p. 40 in Kenneally *et al.* 1996). Seagrass has been absent from Town Beach since we first mapped it in 2000, although some patches seem to have been seen there outside the area we have covered with sampling stations. It is interesting that Aboriginal hunters of dugong are now reporting a increase in dugong numbers after a decline coincident with cyclone Rosita (B. Webster pers. comm.); the dugongs are probably following the recovery of seagrass coverage in Roebuck Bay.

Table 1. Percentage of sites where linear and oval seagrasses were present in 1997, 2002 and 2006, either or not corrected for overlap in sampling sites between the three survey efforts.

Seagrass species	Accounting for overlap?	1997	2002	2006
Linear *Halodula*	No	22	1	11
	Yes	16	1	12
Oval *Halophila*	No	16	1	16
	Yes	15	1	16

Photo 9. The seagrass beds of Roebuck Bay are not very dense, but dense enough to sustain a small population of dugong. This photo was taken in Shark Bay by Jan van de Kam (from Rogers *et al.* 2003).

Which macrozoobenthic taxa did we encounter in the samples in 2006?

A total of 185 different taxa were encountered in the mudcores covering 1/40 m² at 532 sampling stations along the northern shore of Roebuck Bay in June 2006 (Table 2). Most taxa found were encountered during the earlier surveys in Roebuck Bay in 1997, 2000 and 2002 and in the benthic survey of Eighty-mile Beach in 1999 (Piersma *et al*. 2005). Nevertheless, about 26 taxa had apparently not been encountered before. The series of small bivalves belonging to the Galeomnatidae (#1473 to #1509; Table 2) was particularly striking. The relatively strong presence of the very small Galeomnatidae in the samples, and the relative abundance of minuscule transparent organisms such as skeleton shrimps Caprellidae retrieved, also compared to previous years, may indicate that the sorters did an excellent job. In fact, several of the identifiers made remarks to that effect. That the routine of checking each other's trays at the end of each sorting may have made a difference, was also suggested by the fact that over 12,000 individual invertebrates were found in the 532 samples, a number that is similar to the number of animals retrieved from the 1000 sampling stations visited during SROEBIM-02 (Piersma *et al.* 2002). Apart from the miniature snails (Galeomnatidae) the presence of a new kind of large snail, the ornate Ingrid-eating snail *Nassarius bicallosus* now present alongside *Nassarius dorsatus* in different parts of the bay, was quite eye-catching (see below). Two new families of polychaete worms were encountered (Lysaretidae and Poecilochaetidae), and the carpet-forming Tunicates may, or may not, have been encountered before. These animals have few distinctive features and future work needs to elucidate their identity.

The different families of polychaete worms will actually be composed of several different species (S. Dittmann pers. obs.). A collection of specimens in spirits was made in order to be able to assign at least part of the polychaetes to species level. This work will be reported on separately in the future (S. Dittmann in prep.). It is also believed that the group of *Macrophthalmus* or sentinel crabs will be composed of several distinct species; this group urgently needs separate scientific attention as well. The nearshore and beach living fiddler crabs (*Uca* sp.) and ghost crabs (*Ocypode* sp.) were not found in the mudsamples collected, although they were all seen in their normal habitats.

Table 2. Species list of the 185 different taxa of intertidal macrobenthic invertebrates found in the quantitative samples during ROEBIM-06 (not listed are another eleven taxa with uncertain affinities: these were all stored on spirits for later examination by experts).

Spec. #	Name of taxon (*genus* and *species*)	Family/Group	Remarks on identity/pseudonym	#sites	New in 06
1101	*Nucula* cf *astricta*	Nuculidae		8	
1121	*Ledella* spec.	Nuculanidae	? *Nuculana*	5	
1151	*Solemya* cf *terraereginae*	Solemyidae		40	
1201	*Anadara granosa*	Arcidae		6	
1301	*Modiolus micropterus*	Mytilidae		1	
1401	*Anodontia omissa*	Lucinidae		106	
1411	*Divaricella irpex*	Lucinidae	was *ornata*	32	
1421	*Ctena*	Lucinidae	*Bellucina* spec.	27	
1422	*Ctena* 'smooth'	Lucinidae		2	
1461	*Mysella* "curva"	Galeomnatidae		1	
1471	Bivalvia "macrophthalmus"	?Lasaeidae		5	
1473	*Galeomna* sp. 1	Galeomnatidae	Nucula-like	3	yes
1501	*Scintilla*	Galeomnatidae		10	
1503	*Galeomna* sp. 2	Galeomnatidae		2	yes
1504	*Galeomna* sp. 3	Galeomnatidae	Striated	1	yes
1505	*Galeomna* sp. 4	Galeomnatidae	Yellowish	1	yes
1506	*Galeomna* striped	Galeomnatidae	Striped	1	yes
1507	*Galeomna* waved	Galeomnatidae	Waved (with coarse ribs)	3	yes
1508	*Galeomna* juv brown striped	Galeomnatidae		9	yes
1509	*Galeomna* spec 7	Galeomnatidae		3	yes
1605	Juv *Mactra* A	Mactridae		5	yes

1606	Juv *Mactra* B	Mactridae		11	yes
1607	*Mactra* cf *abbreviata*	Mactridae		1	yes
1621	*Mactra grandis*	Mactridae	large brown	4	
1651	*Corbula* spec.	Corbulidae	*Corbula* spec.1	6	
1701	*Cultellus cultellus*	Cultellidae		3	
1711	*Siliqua pulchella*	Cultellidae	was *Siliqua* cf *winteriana*	53	
1801	*Tellina capsoides*	Tellinidae		13	
1802	*Tellina piratica*	Tellinidae		68	
1803	Smooth *Tellina piratica*	Tellinidae	*Tellina inflata*	5	
1804	*Tellina amboynensis*	Tellinidae		31	
1807	*Tellina* pointed	Tellinidae	is spec. 3	7	
1818	*Tellina* "fabula"	Tellinidae	Rechtsgestreept	4	
1819	*Tellina* cf *serricostata*	Tellinidae	juv. *capsoides*?		
1821	*Tellina* cf *exotica*	Tellinidae	*Macoma exotica*	36	
1822	*Tellina exotica* ribbed	Tellinidae			
1823	*Tellina exotica* "rose"	Tellinidae		3	
1824	*Tellina* 'shirley'	Tellinidae			
1825	*Tellina* 'nose'	Tellinidae		1	yes
1826	*Tellina* nose-2	Tellinidae		1	yes
1827	T spec 2006	Tellinidae		2	yes
1828	T spec 2006-2	Tellinidae		1	yes
1829	Texam	Tellinidae		1	yes
1853	*Donax* 2006	Donacidae		1	yes
1871	*Gari lessoni*	Psammobiidae		2	
1872	Sunsetshell-2006-1	Psammobiidae		2	yes
1881	*Solen* spec.	Solenidae		1	
1901	*Anomalocardia squamosa*	Veneridae		34	
1922	*Placamen gravescens*	Veneridae		2	
1923	*Placamen calophyllum*	Veneridae		3	
1932	*Tapes* spec.	Veneridae	*Tapes* spec. 2	1	
1947	Veneridae 2006-A	Veneridae		1	
2001	*Stenothyra* spec.	Stenothyridae	elephant snail	2	
2051	*Clanculus* spec.	Trochidae		1	
2062	*Isandra coronata*	Trochidae	*Umbonium*	1	
2301	*Cerithidea cingulata*	Potamidae	*Cerithium* spec.	18	
2401	Eulimidae	Eulimidae		3	
2501	*Polinices conicus*	Naticidae		9	
2512	*Natica* "with brown band"	Naticidae	*Natica* spec. 2	1	
2551	Columbellidae	Columbellidae		4	
2553	*Nitidella essingtonensis*	Columbellidae	*Mitrella*?	9	
2555	*Zafra* spec.	Columbellidae		11	yes
2601	*Nassarius dorsatus*	Nassariidae	large Ingrid-eating snail	51	
2602	*Nassarius* "small Ingrid"	Nassariidae		7	
2605	*Nassarius bicallosum*	Nassariidae	ornate Ingrid-eating snail	18	yes
2701	Marginellidae	Marginellidae		11	
2751	*Vexillium radix*	Mitridae		3	
2752	*Vexillum* (groot)	Mitridae	Big species	1	
2771	Mitridae	Mitridae		4	
2791	*Oliva australis*	Olividae		1	yes
2801	Turridae	Turridae	Spinally ribbed	8	
2851	Terebridae	Terebridae		3	
2901	*Haminoae* "green"	Haminoeidae		15	
2941	*Acteon* spec.	Acteonidae		2	
2951	*Tornatina*	Cylichnidae	was *Retusa*	14	
2952	Cylichnidae	Cylichnidae	= *Tornatina*	1	
2981	*Salinator* cf *burmana*	Amphibolidae	Mangrove Moonsnail	14	
2991	Pyramidellidae	Pyramidellidae		3	
2992	*Leucotina*	Pyramidellidae		10	
2995	*Syrnola*	Pyramidellidae		1	
3101	*Laevidentalium* cf *lubricatum*	Dentaliidae	Smooth *Dentalium*	53	
3102	*Dentalium* cf *bartonae*	Dentaliidae	Ribbed *Dentalium*	39	
4101	Nemertini	Nemertini		22	
4201	Phoronida	Phoronida		14	
4502	*Sipunculus* "nudus"	Sipuncula		68	
4511	*Phascolion*	Sipuncula	lives in shell	11	
4521	Ringed Sipunculus	Sipuncula		8	
4901	*Balanoglossus*	Enteropneusta		1	
5000	Oligochaeta spec.	Oligochaeta		124	

5001	Polychaeta spec.	Polychaeta		37	
5051	Orbiniidae	Orbiniidae		55	
5121	Polynoidae "red symbiotic"	Polynoidae		107	
5122	Polynoidae spec.	Polynoidae		16	
5151	Sigalionidae	Sigalionidae		34	
5201	Amphinomidae	Amphinomidae	fire worm	55	
5301	Onuphidae	Onuphidae		52	
5305	Eunicidae	Eunicidae		1	
5331	Lysaretidae	Lysaretidae		7	yes
5351	Lumbrineridae	Lumbrineridae		47	
5371	Arabellidae	Arabellidae		1	
5401	Pilargidae	Pilargidae		36	
5411	Hesionidae	Hesionidae		2	
5451	Nereidae	Nereidae	Ragworm	78	
5471	Syllidae	Syllidae		30	
5501	Phyllodocidae	Phyllodocidae		33	
5511	Green Phyllodocidae	Phyllodocidae		28	
5601	Nephtyidae	Nephtyidae	Catworm	247	
5701	Glyceridae (large)	Glyceridae		40	
5711	Glyceridae (small)	Glyceridae		79	
5751	Goniadidae	Goniadidae		143	
5801	Spionidae	Spionidae		149	
5802	Spionidae "red cirri"	Spionidae		3	
5901	Chaetopteridae	Chaetopteridae		63	
5951	Magelonidae	Magelonidae		11	
6001	Cirratulidae	Cirratulidae		54	
6101	Paraonidae	Paraonidae		84	
6201	Opheliidae	Opheliidae		70	
6301	Capitellidae	Capitellidae		165	
6401	Maldanidae	Maldanidae	Bamboo worm	79	
6501	Sternaspidae	Sternaspidae	Mickey Mouse worm	33	
6601	Oweniidae	Oweniidae		119	
6701	Flabelligeridae	Flabelligeridae		1	
6801	Ampharetidae	Ampharetidae		8	
6802	Terebellidae	Terebellidae	Branched tentacles	30	
6811	Trichobranchidae	Trichobranchidae		9	
6851	Sabellariidae	Sabellarriidae		10	
6861	Pectinaridae	Pectinaridae		3	
6901	Sabellidae	Sabellidae		32	
6951	Poecilochaetidae	Poecilochaetidae		1	yes
7101	Ostracoda "oval, smooth"	Ostracoda		195	
7102	Ostracoda "square, sculptured"	Ostracoda		1	
7103	Ostracoda "denticulated"	Ostracoda		5	
7201	*Gammarus*	Amphipoda		102	
7211	Not *Gammarus*	Amphipoda		22	
7221	*Corophium*	Amphipoda		9	
7251	Caprellidae	Amphipoda	Skeleton shrimp	9	
7301	*Anthura* spec.	Isopoda		46	
7311	*Eurydice* spec.	Isopoda		10	
7401	Tanaidacea	Tanaidacea		46	
7501	Cumacea	Cumacea		29	
7502	Anaspidae	Anaspidae		1	yes
7551	Mysidacea	Mysidacea		5	
7601	Squillidae	Stomatopoda	Mantis shrimp	9	
7701	Caridae	Caridea	Shrimp	35	
7751	Alpheidae	Caridea	Pistol shrimp	6	
7901	Hermit crab	Anomura		114	
8051	*Dorippe* cf *australiensis*	Dorippidae		2	
8101	*Matuta planipes*	Callapidae		3	
8201	cf. *Myrodes eudactylus*	Leucosiidae	*Leucosia* A – pebble crab	5	
8221	*Ebalia* spec.	Leucosiidae	*Leucosia* C - no tubercles	3	
8231	*Leucosia* D	Leucosiidae	Polished carapax	12	
8291	Portunidae	Portunidae		2	
8301	*Halicarcinus* cf *australis*	Hymenosomatidae	Spider crab	36	
8311	*Mictyris longicarpus*	Mictyridae	Soldier crab	3	
8501	*Hexapus* spec.	Goneplacidae	Six-legged crab	52	
8601	*Macrophthalmus* spec.	Macrophthalmidae	Sentinel crab	191	
8801	Chironomidae	Insecta	Chironomid larvae	1	

9101	*Edwardsia*	Anthozoa		2	
9102	Sand *Edwardsia*	Anthozoa		1	
9111	Long & slender anemone	Anthozoa		1	
9201	Pycnogonida	Pycnogonida	Sea spider	5	
9301	*Lingula* spec.	Brachiopoda		18	
9401	*Amphiura* spec.	Ophiuroidea	Brittle Star	16	
9402	*Amphiura* (*Ophiopeltis*) *tenuis*	Ophiuroidea		218	
9403	*Amphiura catephes*	Ophiuroidea		148	
9404	*Amphioplus* (*Lymanella*) *depressus*	Ophiuroidea		1	
9405	*Amphioplus* spec.	Ophiuroidea		14	
9406	*Ophiocentrus verticillatus*	Ophiuroidea		3	
9421	*Dictenophiura stellata*	Ophiuroidea	Short-armed Brittle Star	43	
9431	*Ophiocnemis marmorata*	Ophiuroidea		1	
9501	*Astropecten granulatus*	Asteroidea	Starfish	1	
9502	*Astropecten monachanthus*	Asteroidea	Starfish	1	
9551	*Peronella tuberculata*	Echinoidea	Sanddollar	6	
9602	Orange Synaptidae	Holothuroidea		5	
9610	Synaptidae	Holothuroidea		10	yes
9651	*Protankyra verrelli*	Holothuroidea		1	
9701	Rooted Tunicate	Tunicata	Protopolyclinidae/Ritterellidae	26	
9725	Solitary ascidian	Tunicata	Carpet-forming	23	
9726	Small solitary ascidian	Tunicata	Carpet-forming	8	yes
9751	Branchiostoma	Agnatha	*Amphioxus*, lancelet fish	7	
9801	Periophthalmidae	Pisces	Fish/mudskipper	3	
9810	Fish (Gobiidae)	Pisces		8	
9815	Fish	Pisces	Whitefish	1	

Photo 10. A small *Macrophthalmus* sp. or sentinel crab catches the sun. Photo by Eelke Folmer.

Additional benthic beauties

Some of the more distinctive animals encountered in the intertidal habitats of Roebuck Bay are to sparse and too large to turn up in the quantitative samples. To nevertheless underline their presence, we have assembled here some pictures of these benthic beauties. The first beast to be pictured (Photos 11) is a large spider crab that in June 2006 made its first appearance during the BIM-expeditions. *Paranaxia serpulifera* is not a rare beast, however, and is well known to the traditional owners of the bay. In the days after the expedition we found them to be common on a rocky reef at the southern end of Cable Beach. In addition, we also present another large crab (Photo 12), a modern Brachiopod (Photo 13), a sea anemone (Photo 14) and an octopus (Photo 15).

Photos 11. A large spider crab *Paranaxia serpulifera* encountered among the rocks near the spring low-water line south of Quarry Beach. This spider crabs belong to the family Majidae, known otherwise as the true spider crabs, masking crabs or decorating crabs. The latter name refers to their habit of decorating themselves with their claws, actively attaching algae, sponges or hydroids to the hooked hairs covering their carapace. *Paranaxia serpulifera* occurs widespread from the intertidal to depths of ca. 30 m from Perth all the way to northern Queensland. Photo by He Wenshan (Pearl).

Photo 12. This 10 cm wide box crab *Calappa philargius* was encountered near the spring low water line on an area of mudflat south of the mangroves just west of Quarry Beach that for 30-60% was covered with mats of solitary tunicates. This species belongs to the Calappidae, that go under the English name of 'shame-faced crabs' as well as 'boxer crabs'. The back-edge of the carapace of this species, that is 'seldom seen but occasionally brought up in trawls' according to Jones & Morgan (1994), featured a series of blunt spines that help the crab to 'grip' the sand to bury itself, as it does here. Photo by Nicholas Branson.

Photo 13. This is a large *Lingula* sp., a modern representative of the ancient phylum of Brachiopoda or 'lamp-shells'. Unlike bivalves, which have a right and a left valve, brachiopods have a lower and an upper valve, with the upper valve leaving room at the tip for a stalk with which the brachiopods attach themselves to something hard in the substrate. The opening of this stalk at the pointed end of the two valves is reminiscent of the classic oil lamps and gives the group their common name. Like many bivalves, they are suspension feeders. Photo by Jan Drent.

Photo 14. Sea anemone *Cerianthus* (Anthazoa; taxon #9121; Table 2) is an anemone that lives in tubes in soft-sediments. Often *Cerianthus* share their tubes with the representatives of the phylum Phoronida, worm like creatures that usually are black. Photo by Jan Drent.

Photo 15. This is the small octopus that is quite common near and under the rocks scattered in many parts of the mudflats along the northern shores of Roebuck Bay. Photo by Jan Drent.

Nassarius Ltd: a 10 year history of Ingrid-eating snails

As we have seen above, the surface presence of Ingrid-eating snails *Nassarius dorsatus* as recorded on the field sheets bears little resemblance to the distribution measured by the mudcores. Nevertheless, when we compare the distributions of Ingrid-eating snails in 1997, 2002 and 2006 (Fig. 12), the patterns are pretty comparable: occurring everywhere with the higher densities in the softer muds in the Crab Creek corner and near the mangroves at Dampier flats near the entrance of Dampier Creek. There is a suggestion that densities were higher in 1997 than in either 2002 or 2006.

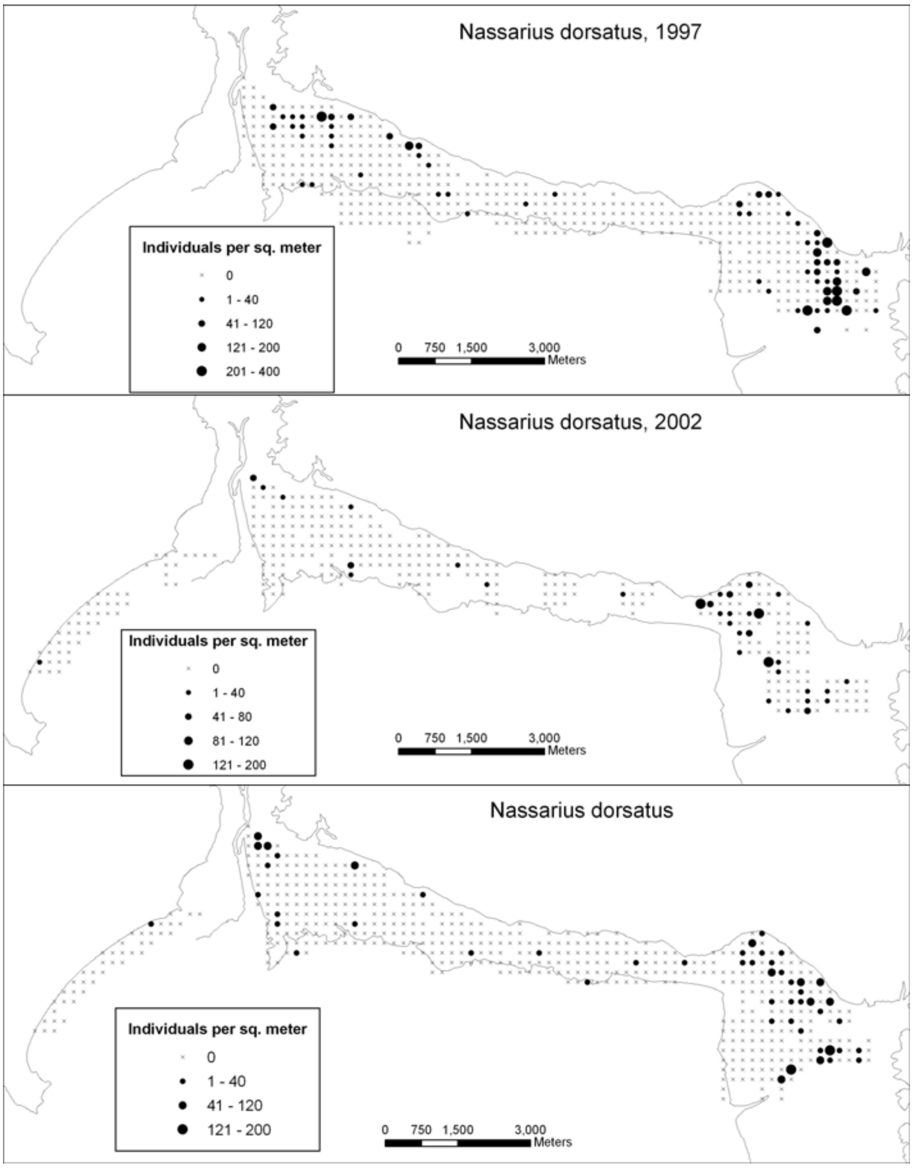


Fig. 12. Occurrence of Ingrid-eating snails *Nassarius dorsatus* in 1997 (top), 2002 (middle) and 2006 (lower panel) based on the core-sampling efforts in these three June-months. Sampling effort is indicated by the circles and the letter 'x' which indicates stations where the snails were not found in a sampled surface of 1/40 m².

The small Ingrid-eating snail in 2006 (Fig. 13 top) showed the same nearshore distribution in quite muddy places that it had shown in both 1997 and 2002, but what really changed between 2002 was the sudden appearance of a third *Nassarius* species, that of *Nassarius bicallosus*. This snail quite similar to *Nassarius dorsatus* (Photo 16), with a quite similar distribution (Fig. 13 lowest panel). The newcomer is an intriguing addition to the bay, and it remains to be seen whether it will compete with *Nassarius dorsatus*, or is actually feeding on different food types.

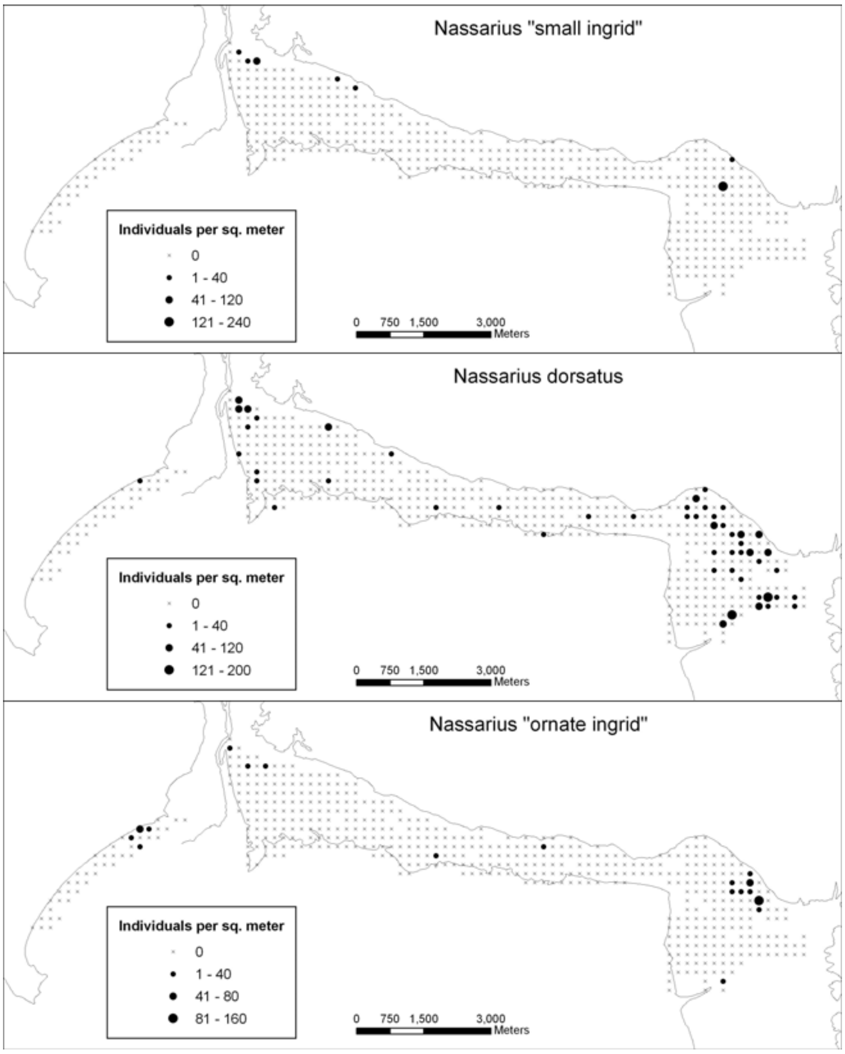


Fig. 13. Occurrence of the three species of Ingrid-eating snails *Nassarius* sp. in June 2006 based on the core-sampling efforts. As usual, small Ingrids were found on a few nearshore stations close to the mangroves, but the 'ornate Ingrid' *Nassarius bicallosum* was only found in June 2006. This species is quite similar to *Nassarius dorsatus*, but has a strongly overlapping distribution on and in the Crab Creek muds.

Photo 16. A photographic comparison between the two large Ingrid-eating snails, *Nassarius dorsatus* on the left and *Nassarius bicallosus* on the right; photographed on Town Beach on 30 June by Jan Drent.

Holding their own: site-faithfulness in bivalves

One of the strikingly abundant and distinctive species of the deep blue mud in the Crab Creek corner in 1997 was the small and thin-shelled bivalve *Siliqua pulchella*. Although fast-moving, they seemed the ideal 'fast' food of the molluscivore shorebirds of the bay. When we repeated the surveys in 2000 (not shown) and 2002 (Fig. 14) we still encountered *Siliqua* mostly in the soft muds near Crab Creek, but at far lower densities. This decline was also apparent in the MONROEB benthic monitoring data collected over the same period of time (de Goeij *et al.* 2003). This year's survey

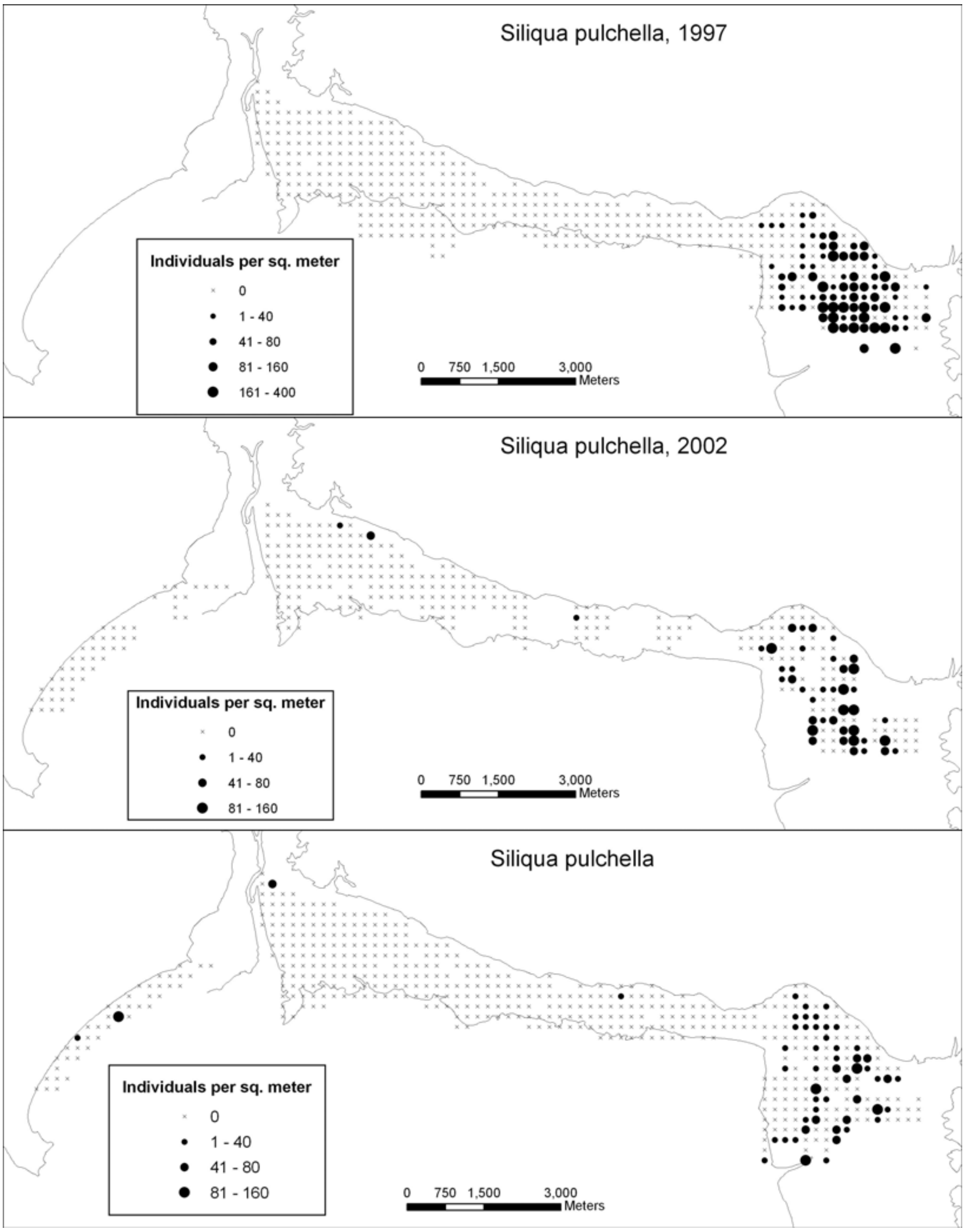


Fig. 14. Quantitative distribution of *Siliqua pulchella* across the northern intertidal of Roebuck Bay in June 1997 (top), June 2002 (middle) and June 2006 (bottom panel). Sampling stations without *Siliqua* are indicated by the letter 'x'.

confirmed the presence of *Siliqua* in the Crab Creek corner muds, in densities quite similar to those in 2002 (Fig. 14 lowest panel). *Siliqua* may change density, but hardly seems to change distribution. It this pattern of relative site-faithfulness that seems to be characteristic of most of the common Roebuck Bay bivalves for which the data are open to examination now.

The first bivalve species that is available for comparison is the tellinid *Tellina capsoides* (Fig. 15). In all three years *T. capsoides* occurred high on the Dampier Flats, and in both 1997 and 2006 it also occurred high in the intertidal in the Crab Creek corner where it went missing in 2002.

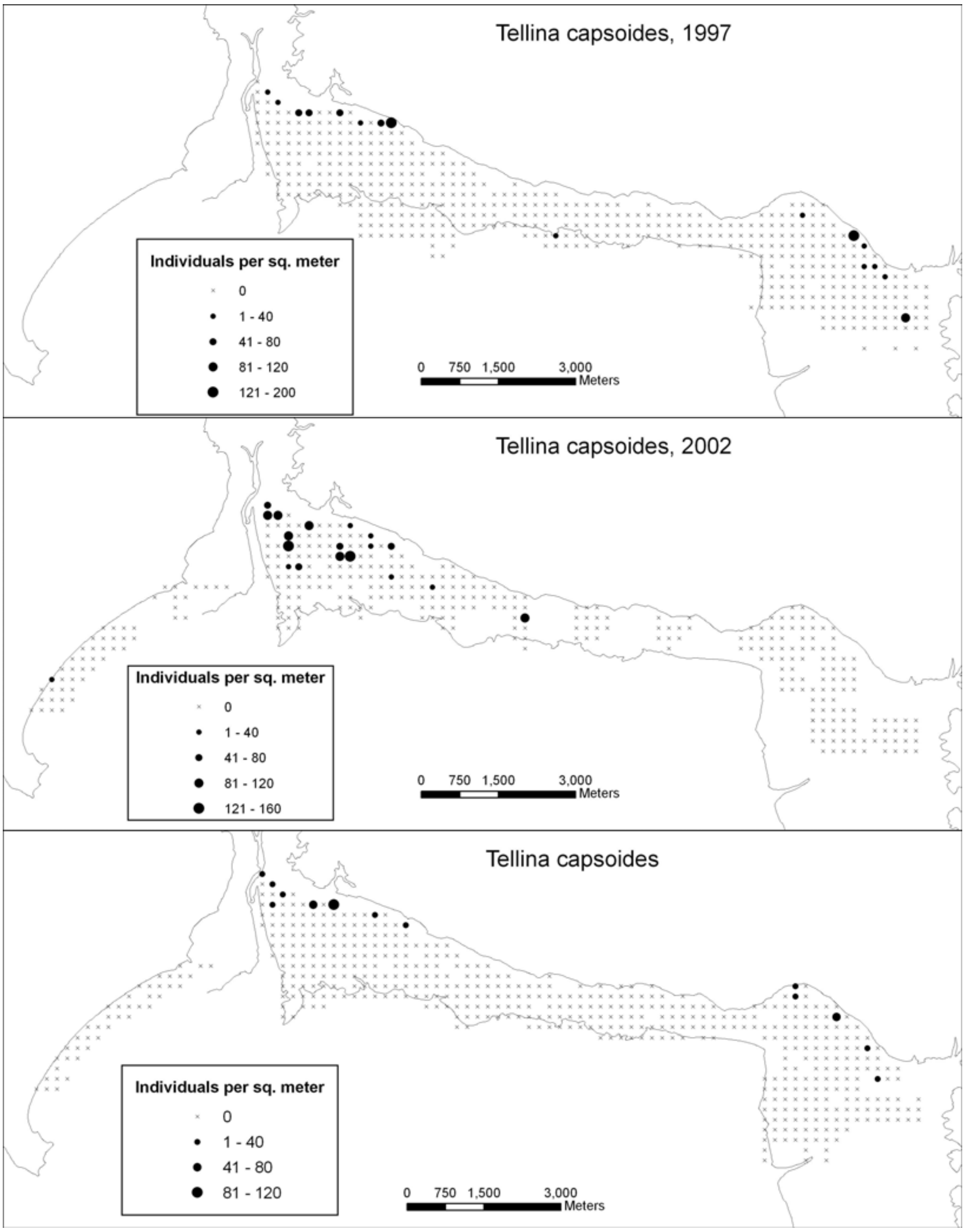


Fig. 15. Quantitative distribution of *Tellina capsoides* across the northern intertidal of Roebuck Bay in June 1997 (top), June 2002 (middle) and June 2006 (bottom panel). Sampling stations without *T. capsoides* are indicated by the letter ‘x’.

The closely related tellinid *Tellina piratica* occurred in large densities across the middle northern shore in June 1997 (Fig. 16 top), at similar spots but at much lower densities in June 2002 (but note their stark presence on Town Beach; Fig. 16 middle panel), a distribution pattern that resurfaced in June 2006, although with slightly increased densities on Dampier Flats (Fig. 16 bottom). In June 2006 densities of *T. piratica* at Town Beach seem to have decreased a little relative to 2002, but overall their distributions were similar.

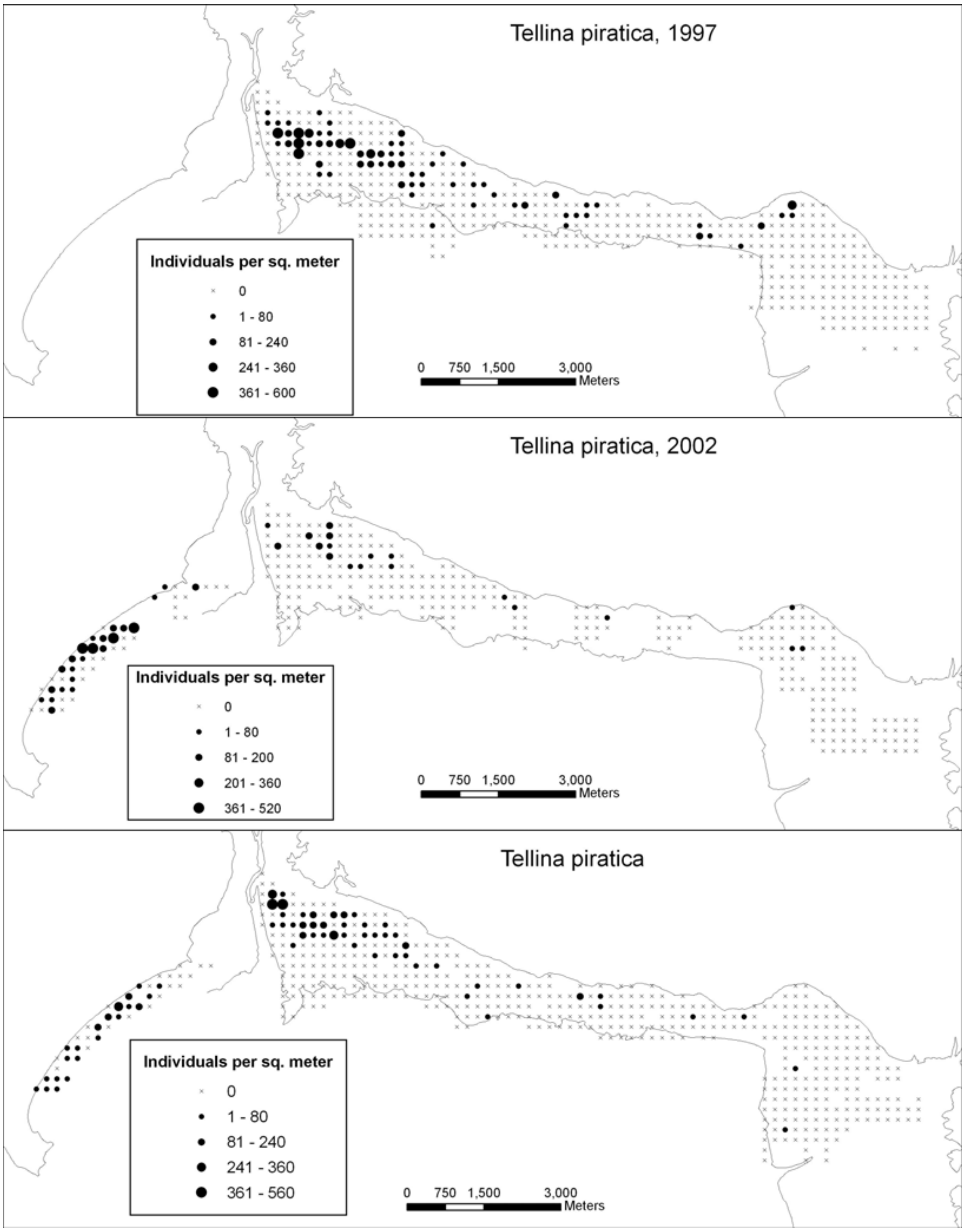


Fig. 16. Quantitative distribution of *Tellina piratica* across the northern intertidal of Roebuck Bay in June 1997 (top), June 2002 (middle) and June 2006 (bottom panel). Sampling stations without *T. piratica* are indicated by the letter ‘x’.

A third tellinid bivalve, *Tellina amboynensis*, in 1997 shared the soft muds of the Crab Creek corner with *Siliqua pulchella* (Fig. 17 top), and in fact does so to the present day (Fig. 17 mid and bottom)! As with *Siliqua*, densities of *T. amboynensis* were somewhat lower in 2002 and 2006 than in 1997, and *T. amboynensis* seem to have a slightly more lower shore distribution in the more recent years. Apart from the Crab Creek corner, *T. amboynensis* has shown up in a few muddy spots on the upper Dampier Flats in all three surveys.

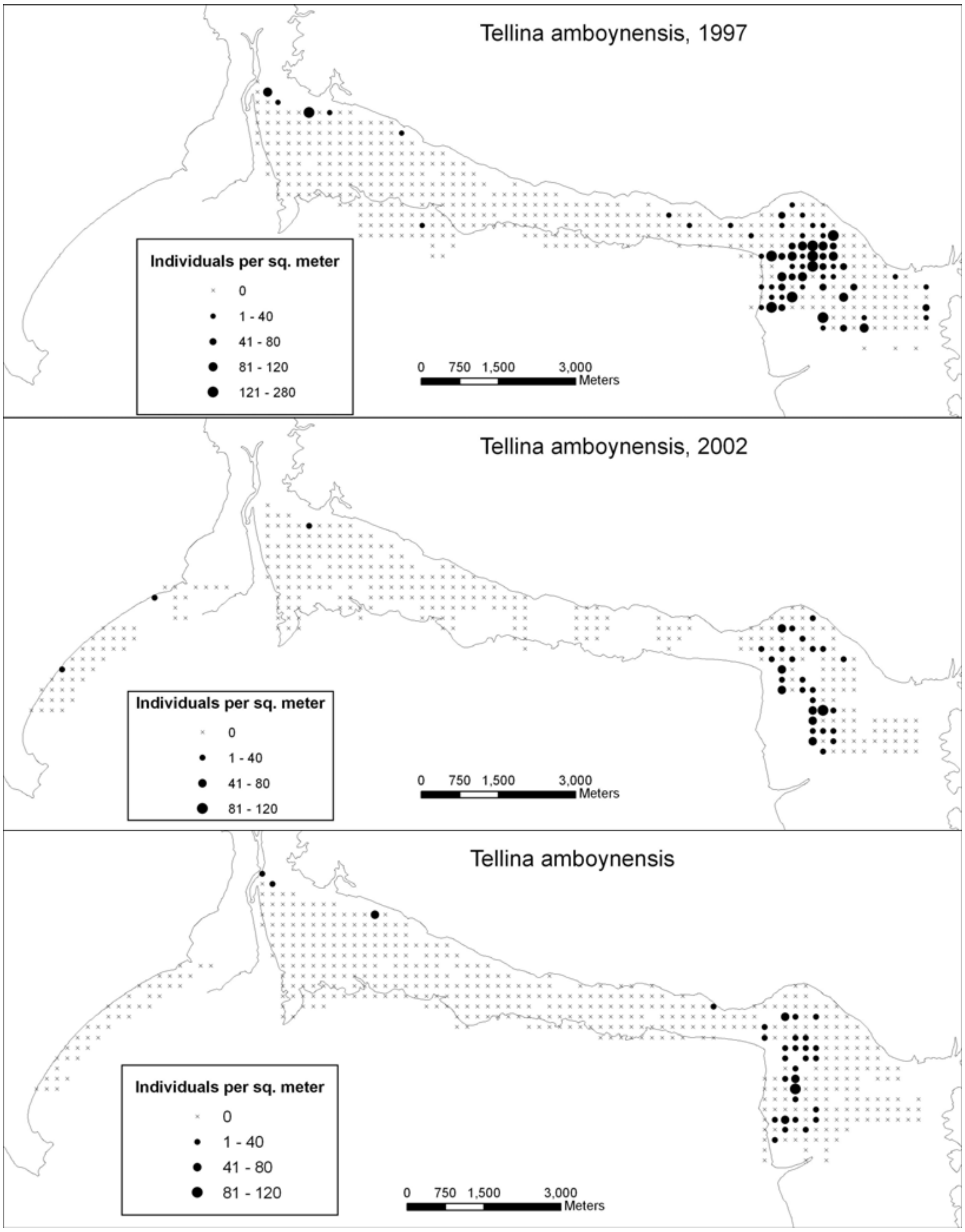


Fig. 17. Quantitative distribution of *Tellina amboynensis* across the northern intertidal of Roebuck Bay in June 1997 (top), June 2002 (middle) and June 2006 (bottom panel). Sampling stations without *T. amboynensis* are indicated by the letter 'x'.

Like the previous two tellinids, *Tellina* cf *exotica* was more common in 1997 than in 2002 or 2006 (Fig. 18), but as in all bivalves examined so far, their overall distribution across the northern shore is very similar. More wide and thinly spread than the previous three tellinids, *T.* cf *exotica* occurs over a wide range of sediment types, from the deep muds of the Crab Creek corner to the sandy muds of Town Beach. Whether this reflects important intraspecific variation or whether we have identification problems with this species, remains to be seen. DNA samples were collected in 2006 to verify the identifications made on the basis of the morphological characteristics of the shells.

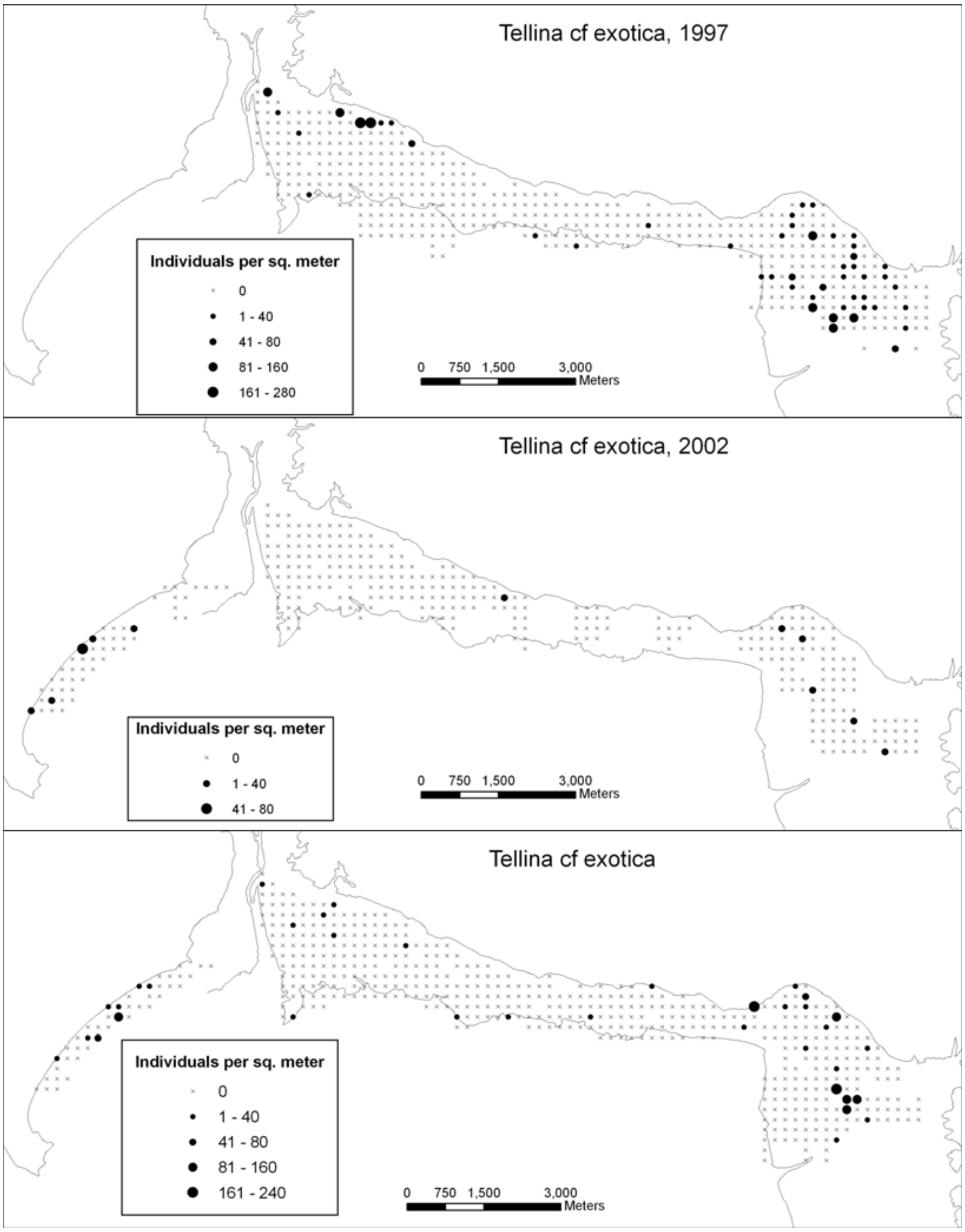


Fig. 18. Quantitative distribution of *Tellina* cf *exotica* across the northern intertidal of Roebuck Bay in June 1997 (top), June 2002 (middle) and June 2006 (bottom panel). Sampling stations without *T.* cf *exotica* are indicated by the letter 'x'.

The venerid *Anomalocardia squamosa* has the short fused siphon typical of suspension-feeders (and unlike the long separate inhalent and exhalent siphons that characterise deposit feeders like tellinids). It shows a distribution pattern (Fig. 19) that is consistent between the three years and quite similar to the distribution of *T. piratica* (Fig. 16). *Anomalocardia* consistently occurred in highest densities on the middle and higher parts of Dampier Flats and also on Town Beach, with slightly reduced densities in 2002 and 2006 compared with 1997.

In summary, in all six suspension-feeding (*Siliqua* and *Anomalocardia*) and deposit-feeding (*Tellina*) bivalves, the spatial distributions have been remarkably comparable between years. Given the stark and repeatable gradients in sediment type (see data on penetrability in Fig. 5) and tidal height (reflecting emersion times; T. Compton *et al*. in prep.) this is perhaps not surprising, but given their wide distributions across these gradients and variable recruitment patterns (de Goeij *et al*. 2003) perhaps it is.

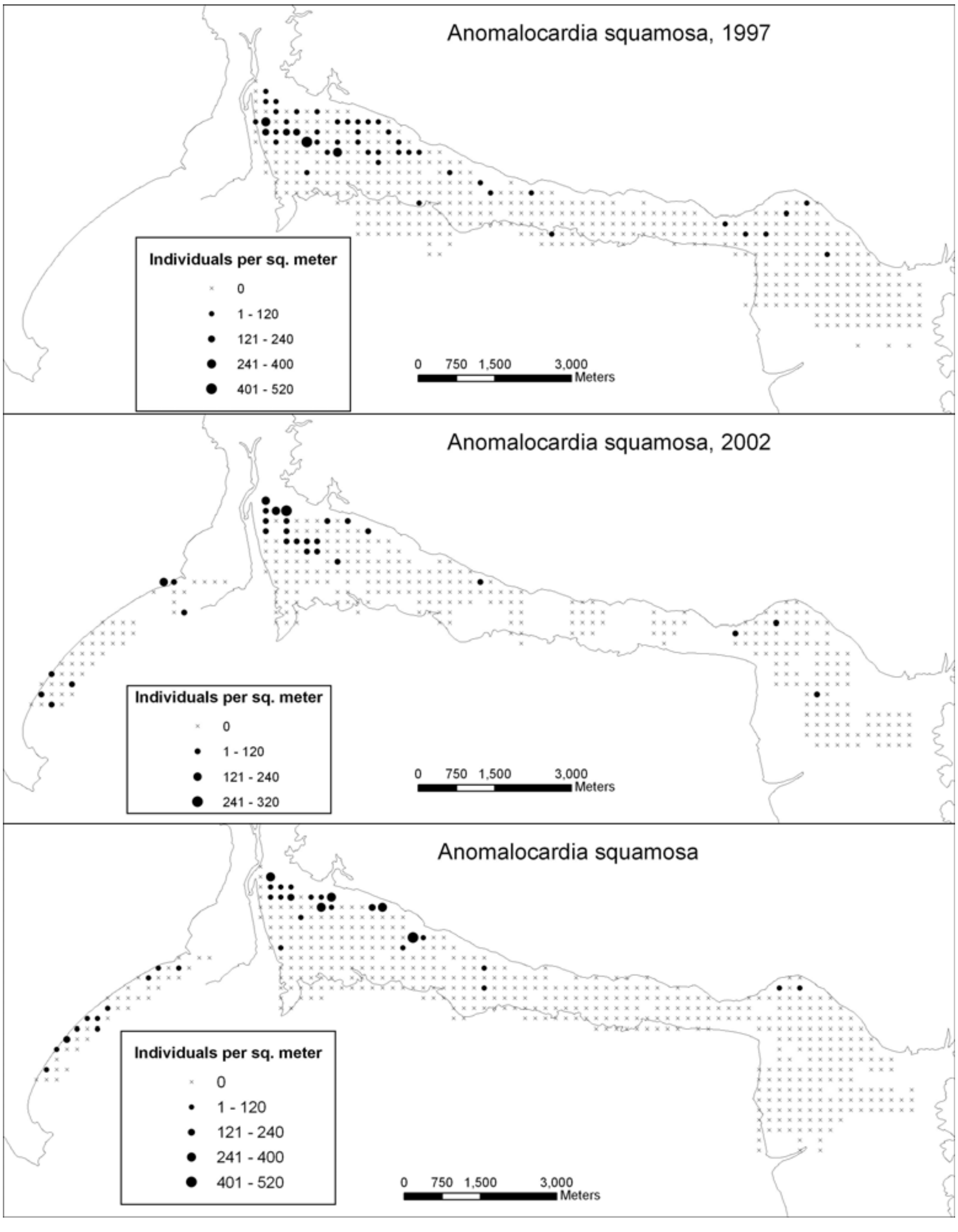


Fig. 19. Quantitative distribution of *Anomalocardia squamosa* across the northern intertidal of Roebuck Bay in June 1997 (top), June 2002 (middle) and June 2006 (bottom panel). Sampling stations without *Anomalocardia* are indicated by the letter ‘x’.

The decline of the bloody cockle

Arguably the most widely known, and traditionally the most important, bivalve of Roebuck Bay is the bloody cockle *Anadara granosa*. Middens surrounding the bay testify to the importance of this benthic invertebrate for local Aboriginal communities into the depths of time. During the first survey in 1997, cockles were found in good densities near the mangroves on the higher Dampier Flats and on the nearshore parts of the Crab Creek corner (Fig. 20 top). Indeed, it was common to see local people collecting cockles in the latter area. By 2002 the cockles had become very rare (Fig. 20 middle) and the situation has not changed in the four years to 2006 (Fig. 20 bottom). It remains a mystery as to why *Anadara* has not shown a come-back (in the case of overharvesting of adult sized cockles we would still expect to find plenty of juveniles), but note that their relatively high numbers in 1997 is consistent with the peak abundance's of several other bivalves in 1997. However, we know that bloody cockles occurred in similar or higher (harvestable) densities prior to 1997.

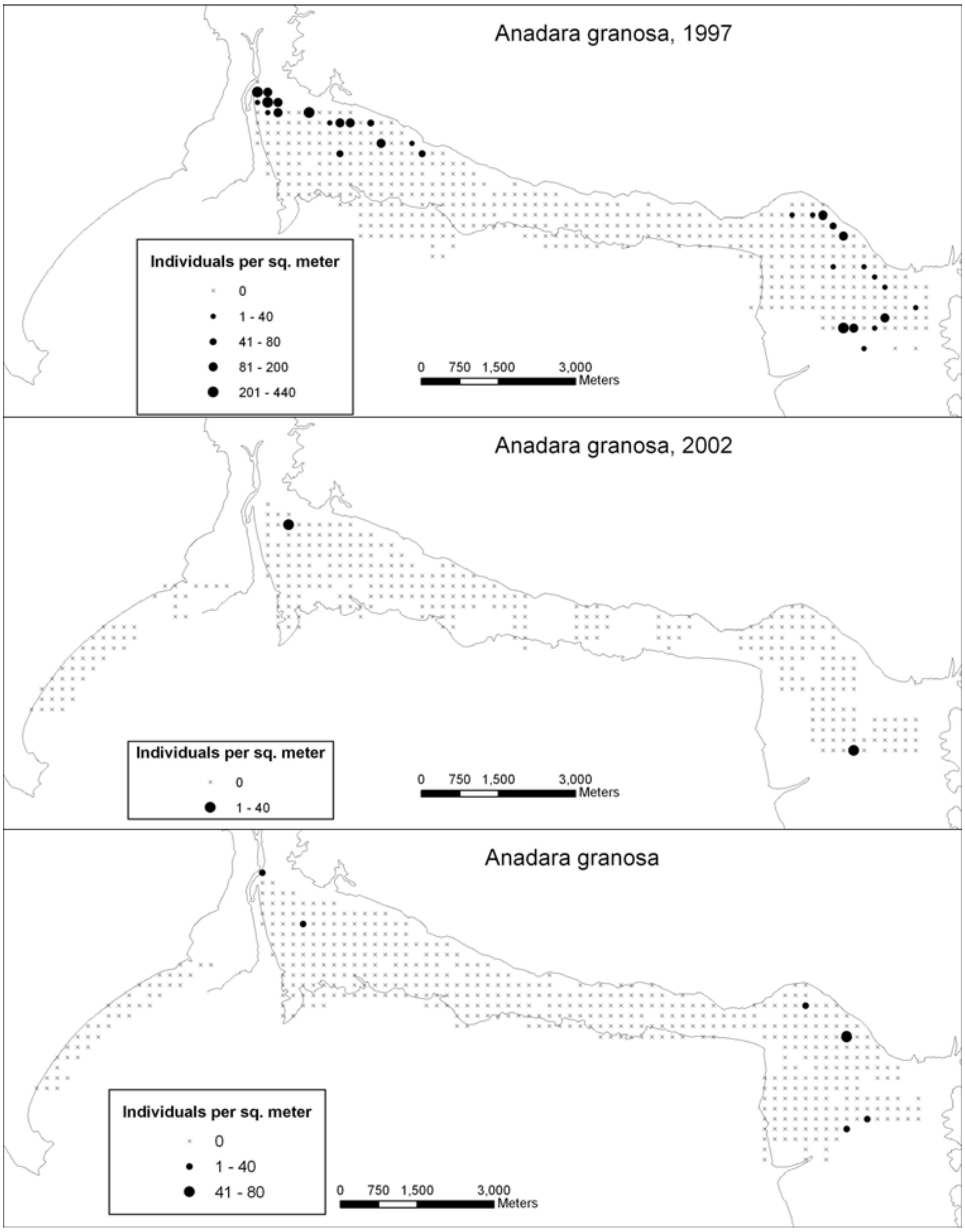


Fig. 20. Occurrence of bloody cockles *Anadara granosa* in June 1997 (top), 2002 (middle) and 2006 (bottom) based on the core-sampling efforts.

Puncturing the mud: scaphopods, the tuskshells

Tuskshells or Scaphopoda is one of the smaller mollusc classes, withg only a few hundred species. Most of the species live in deep offshore waters (Edgar 1997). They have curved tubular shells that tapers toward one end. Their head and wedge-shaped foot extends from the wide end of the shell that is buried deep in the sediment; the narrow top end projects above the mudsurface. It is through this narrow pipe that water for respiration is passed in and out.

Of the three species found on the intertidal flats of Roebuck Bay, one, *Cadulus* sp., is very small. The two larger, 1-5 cm long, species are pretty similar, but one has a smooth and the other a ribbed surface; they belong to two different genera. The smooth tuskshell *Laevidentalium* occurs widespread over all parts of the intertidal flats, living in very muddy as well as quite sandy places (Fig. 21 top). The ribbed tuskshell *Dentalium* only occurs at the muddier sites in the Crab Creek corner and in the muds near Dampier Creek and the nearby mangal edge (Fig. 21 bottom).

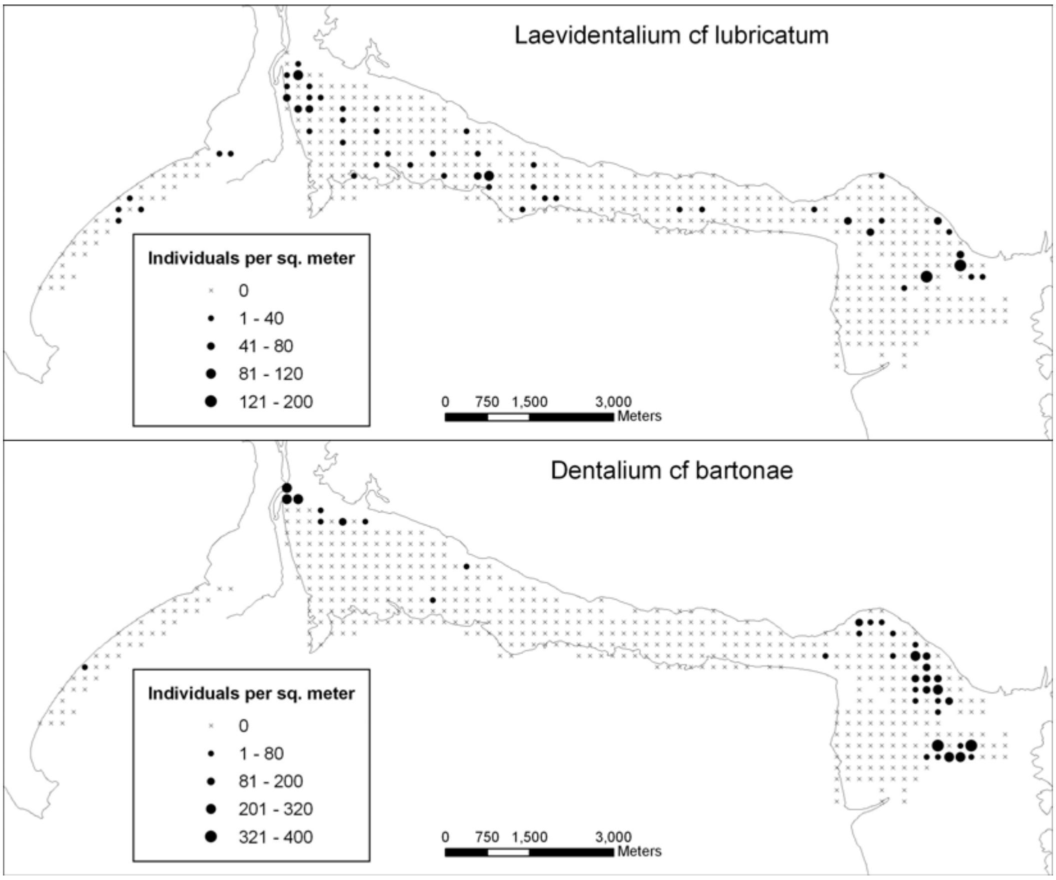


Fig. 21. Occurrence of the smooth tuskshell *Laevidentalium* cf *lubricatum* (top) and the ribbed tuskshell *Dentalium* cf *bartonae* (bottom) in June 2006 based on the core-sampling efforts.

A brief brittlestarry tale: how similar echinoderms share intertidal space

One of the most widespread invertebrates of the intertidal flats of Roebuck Bay are the brittlestars; in June 2006 they were encountered at over half of the sampling stations. Brittlestars may live in quite different ways, with the short-armed brittlestar *Dictenophiura stellata* living on the sediment surface, unlike the *Amphiura* species that live deeply buried in the sediment with their long brittle arms stretching to the surface to catch food particles. Short-armed brittlestars, perhaps not surprisingly, occurred only on the lower flats: they occurred only on the sandy flats off the Dampier mangroves and Quarry Beach (Fig. 22).

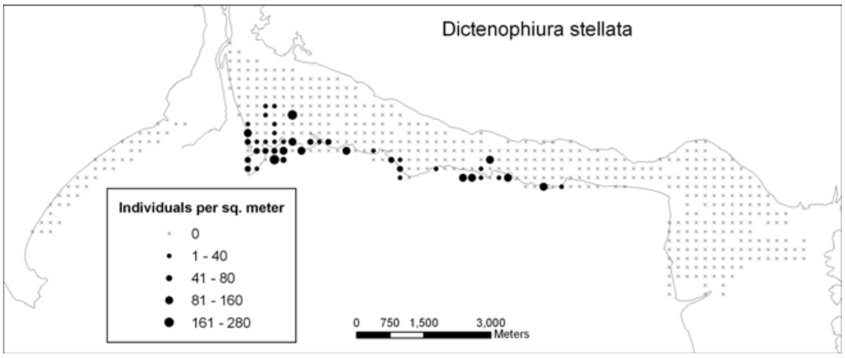


Fig. 22. Occurrence of short-armed brittlestar *Dictenophiura stellata* across the northern intertidal flats of Roebuck Bay in June 2006 based on the core-sampling efforts.

The long-armed brittle stars *Amphiura* sp. occurred higher up on the flats (Fig. 23). They are among the most widespread species of the bay. Despite, or due, to their similarity, *Amphiura tenuis* and *Amphiura catephes* usually occurred together, *A. catephes* being the less numerous species and largely absent in the soft muddy areas of Crab Creek Corner.

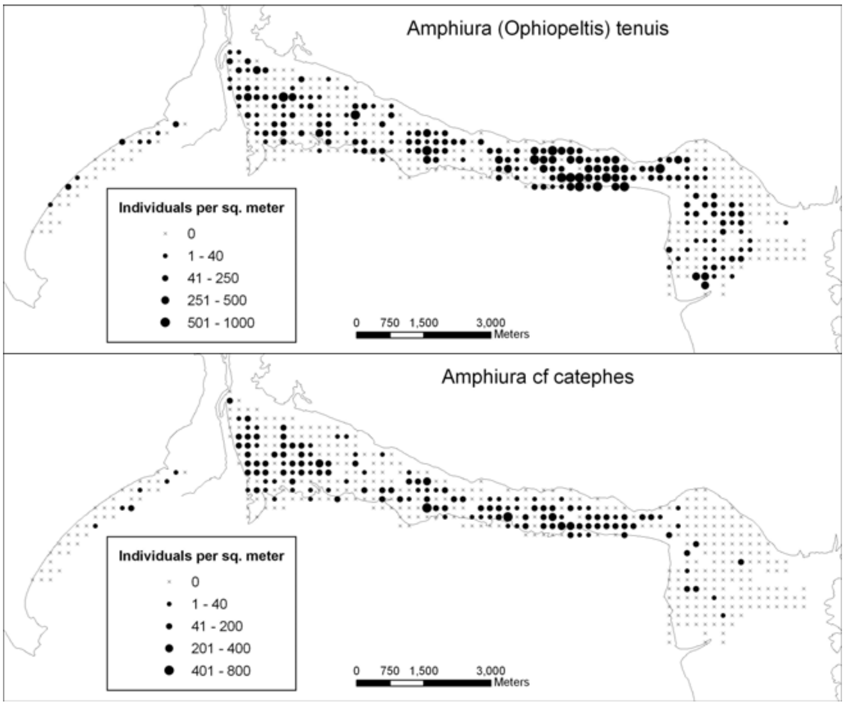


Fig. 23. Occurrence of two very similar species of brittlestars: *Amphiura tenuis* (top) and *Amphiura catephes* (bottom) across the northern intertidal flats of Roebuck Bay in June 2006 based on the core-sampling efforts.

Widespread worms

Polychaete worms as a group are a bit of an 'acquired taste': polychaete lovers and connoisseurs are thin on the ground, and even these specialists have problems in easily assigning species names to the individuals, or the parts of individuals, found. Part of the problem may be that a fair percentage of the polychaete worms of intertidal flats in this corner of the world remain undescribed and unnamed, but it certainly also takes much time, skill and the availability of handbooks and specialised publications to make the species assignments. For the mapping surveys, from the very start in 1997, we have chosen to identify polychaete worms to family level. During the present survey much material was collected which should enable S. Dittmann to make a start with species designations.

Figure 24 shows the distribution of a species, rather than a family. It concerns an as yet unnamed member of the Polynoidae family, and this 5-6 mm short little red polychaetes is believed to live symbiotically, or commensally, in the burrows made by the arms of the amphiurid brittlestars (see Fig. 23). Indeed, the distribution of the red polynoids, by and large overlaps with the distribution of amphiurids, although polynoids were not found at each of the sampling stations where amphiurids occurred. Before too long we hope to analyse the co-occurrence of these worms and the two kinds of brittlestars in more detail, both in Roebuck Bay and along the Eighty-mile Beach foreshore.

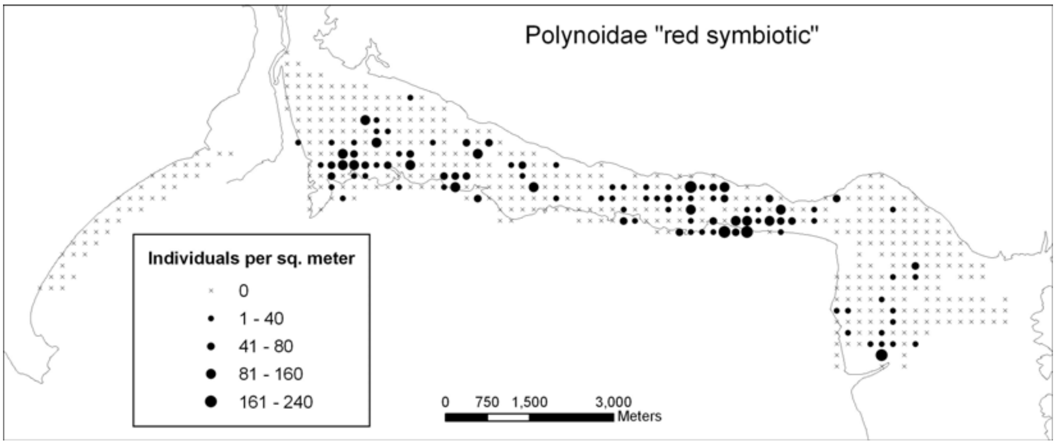


Fig. 24. Distribution across the northern intertidal flats of Roebuck Bay in June 2006 of the red-coloured members of the polychaete family Polynoidae that live symbiotically with brittlestars, based on the core-sampling efforts.

We will now show some examples of the distributions of different families of polychaete worms, bearing in mind that each of these families may be represented by different species in different locations. Indeed, it is quite striking that all family distribution maps presented (Figs. 25-29) show particularly wide ranges, the polychaete taxa seemingly occurring over much broader ranges of sediment types and tidal heights than the bivalve species discussed above. These widespread distributions could perhaps be explained by being the result of the summation of much more limited species-specific distributions.

The first example (Fig. 25) is of the family Syllidae, a kind of worm that shows a sparse, but widespread occurrence across the northern intertidal flats of Roebuck Bay with the highest densities at Town Beach in the west. The Nephthyidae (Fig. 26) are a family of long and slender and agile predatory polychaetes. They are widespread, but do not occur offshore in the Crab Creek corner. Highest densities are reached ad the midshore levels off Quarry Beach. The Spionidae (Fig. 27) are just as widespread, but much thinner on the ground that the nephtids. The offshore area off Quarry Beach and areas near the Broome Bird Observatory showed the greatest densities.

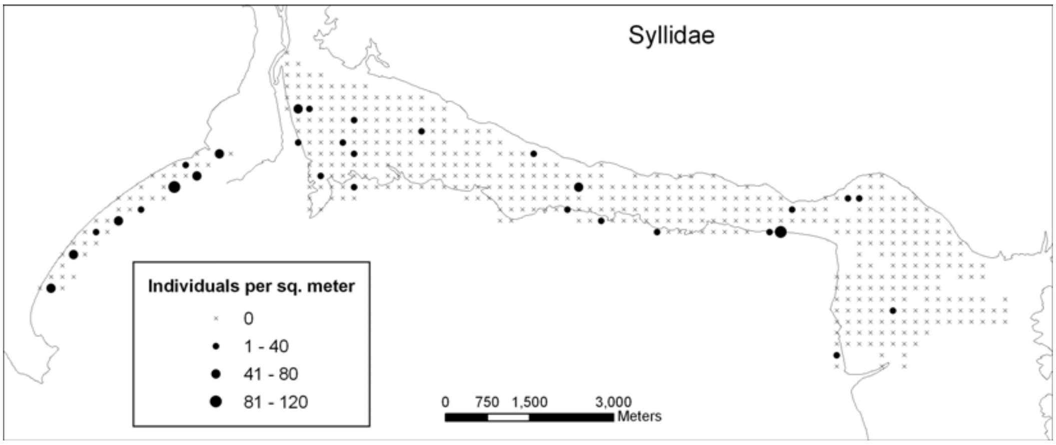


Fig. 25. Distribution of the polychaete family Syllidae across the northern intertidal flats of Roebuck Bay in June 2006 based on the core-sampling efforts.

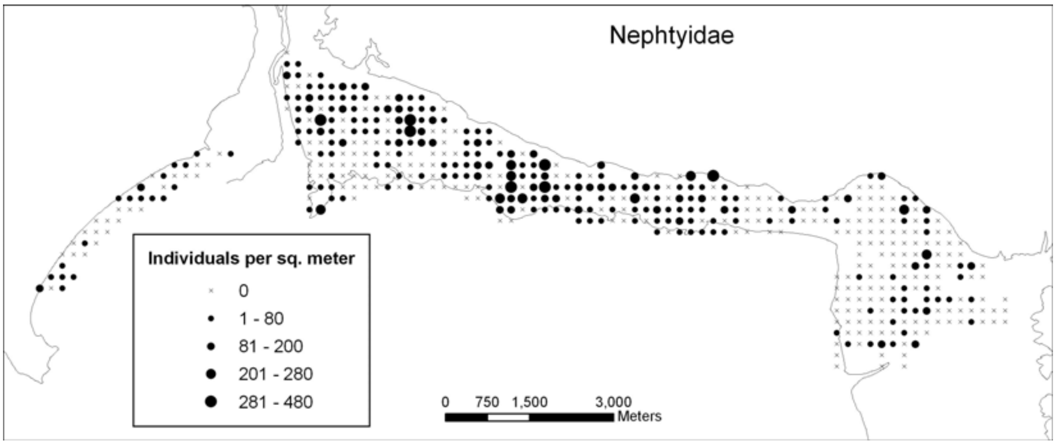


Fig. 26. Distribution of the polychaete family Nephthyidae across the northern intertidal flats of Roebuck Bay in June 2006 based on the core-sampling efforts.

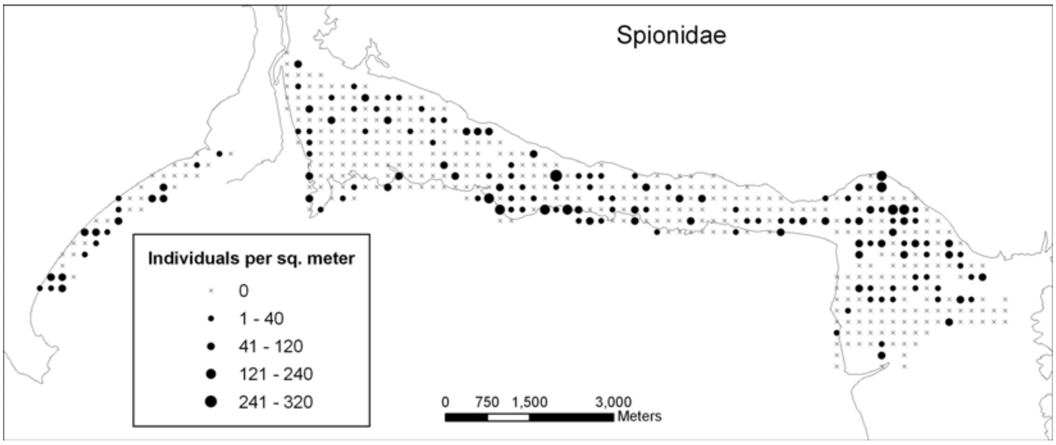


Fig. 27. Distribution of the polychaete family Spionidae across the northern intertidal flats of Roebuck Bay in June 2006 based on the core-sampling efforts.

The Oweniidae are tubeworms with greyish tubes that come in a wide range of lengths. They were very abundant along the sandy northern shores during the first benthic survey in 1997 (Pepping *et al*. 1999). Since, they have declined greatly and now show the highest densities in the lower shore areas around Crab Creek (Fig. 27). It is striking that the Oweniidae have such a downshore distribution in the Crab Creek corner, as they seem to be living on the highest parts of the intertidal flats elsewhere along the northern shores. The contrast may well reflect the presence of different species with different habitat requirements.

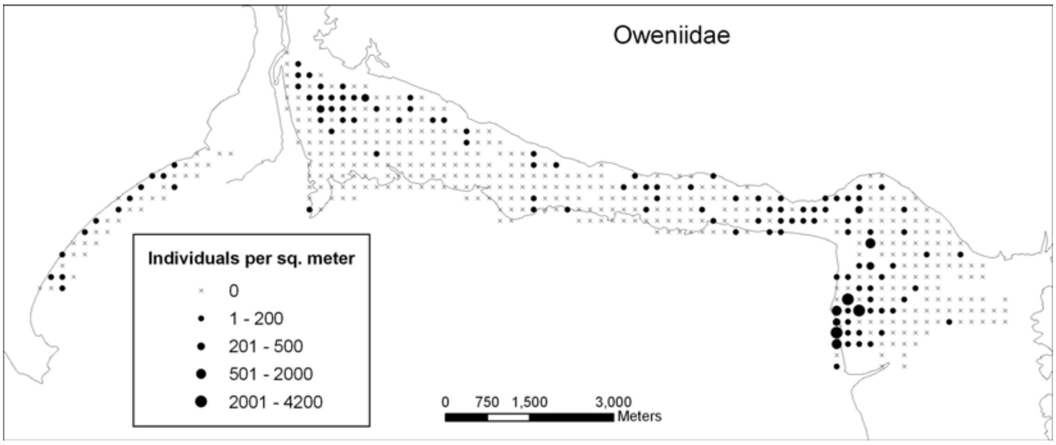


Fig. 28. Distribution of the polychaete family Oweniidae across the northern intertidal flats of Roebuck Bay in June 2006 based on the core-sampling efforts.

Another group of polychaete worms that has shown considerable changes in abundance (but not so much in distribution) over the years are the Glyceridae and the related family of Goniadidae (the latter were not separately assigned in 1997 and 2002). Glycerids are red agile predators with the ability to 'catapult out' their jaws to catch invertebrate prey. They were very widespread and very common in June 1997 (Fig. 28 top), but occurred in much smaller numbers in June 2002 (Fig. 28 middle), then hardly being found in the middle section of the northern foreshore. They were more widespread and numerous again in 2006.

It is tempting to think that their abundance is related to (or even determined by) the presence of tube-living polychaetes like the Oweniidae and the 'plastic worms' Chaetopteridae. These groups were particularly abundant in June 1997 (much to the agony of the sorters who had to go through great masses of rapidly rotting tubeworms; Pepping *et al*.

1999), and were much reduced in numbers by 2002 (Piersma *et al*. 2002; and see de Goeij *et al*. 2003 who were able to document this trend at the monitoring sites). That the abundance of glycerids followed these trends up to 2006 (to be analysed and documented in much more detail later) is suggestive of process where predators follow the abundance of their prey. This has been documented for the Dutch Wadden Sea, where a species of Nephthyidae (*Nephthys hombergii*) follows the abundance an Orbiniidae species, *Scoloplos armiger* (Beukema *et al.* 2000).

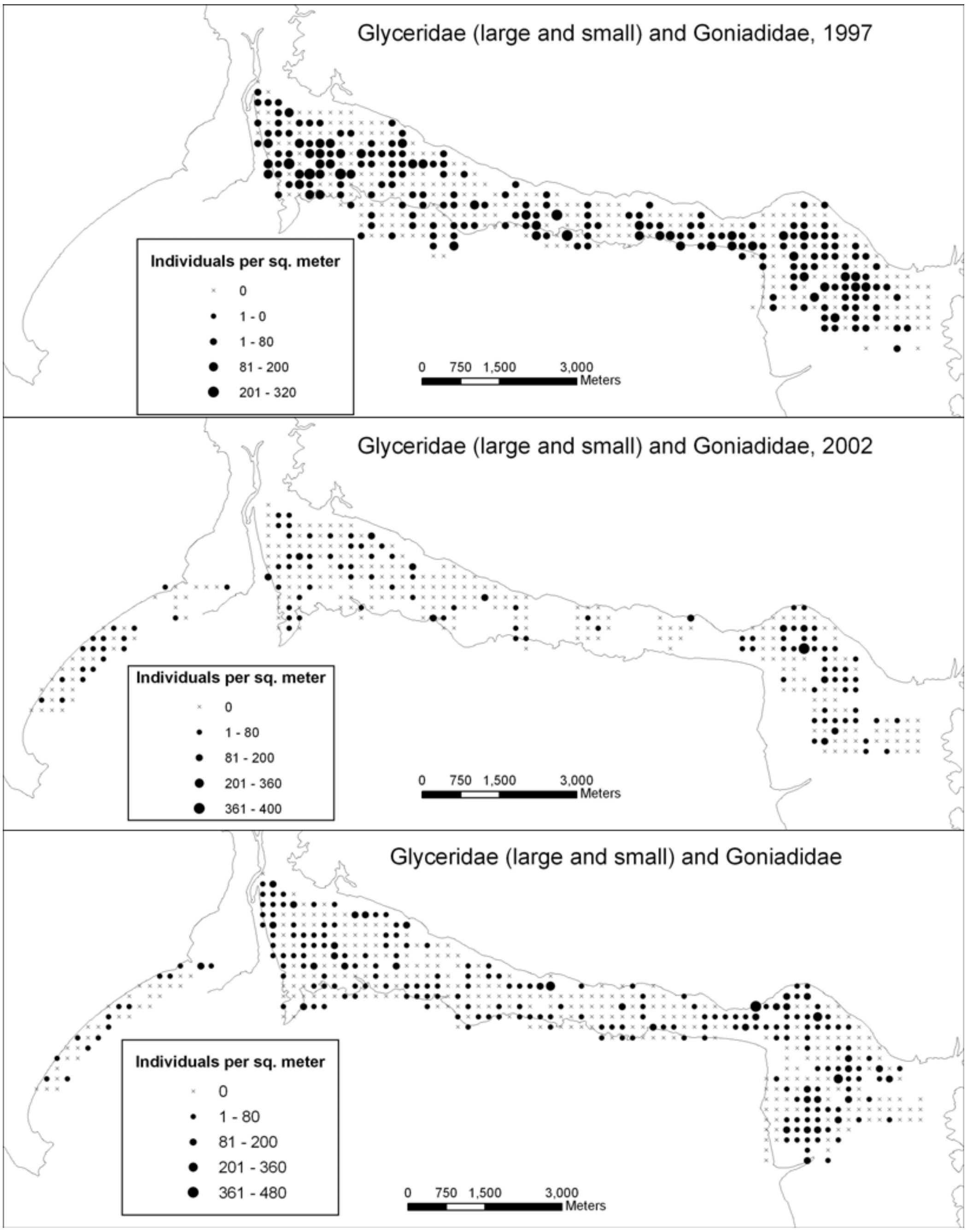


Fig. 29. Occurrence of the predatory worms belonging to the families Glyceridae and Goniadidae in June 1997 (top), 2002 (middle) and 2006 (bottom) based on the core-sampling efforts.

Nudity on the lower beach: sipunculids in the surf

There is one invertebrate that invariably elicits the giggles of even the most serious sorters around the sorting table. The flesh-coloured sipunculids (phylum Sipuncula) change body shape and stiffness in ways that are almost too good to be true. Although commonly named peanut worms in English, they usually end up with a different, though not very dissimilar name, in the camp (Photo 17).

Photo 17. A 2 cm long, but extendable, sipunculid, or peanut worm, taken out of its natural soft-sediment habitat and photographed on a piece of sandstone by Jan Drent.

Sipunculids, unlike polychaete worms, are unsegmented and rather leech-like animals. Only about 300 species are known (Edgar 1997), and one of them, named *Sipunculus* '*nudus*' for the time being, occurs quite wide-spread over the lower foreshores of northern Roebuck Bay (Fig. 30). They excavate temporary burrows in the sand, and use their extendable trunk (not shown on Photo 16, but about to appear on the left-hand end) to forage on organic material on and in the mud.

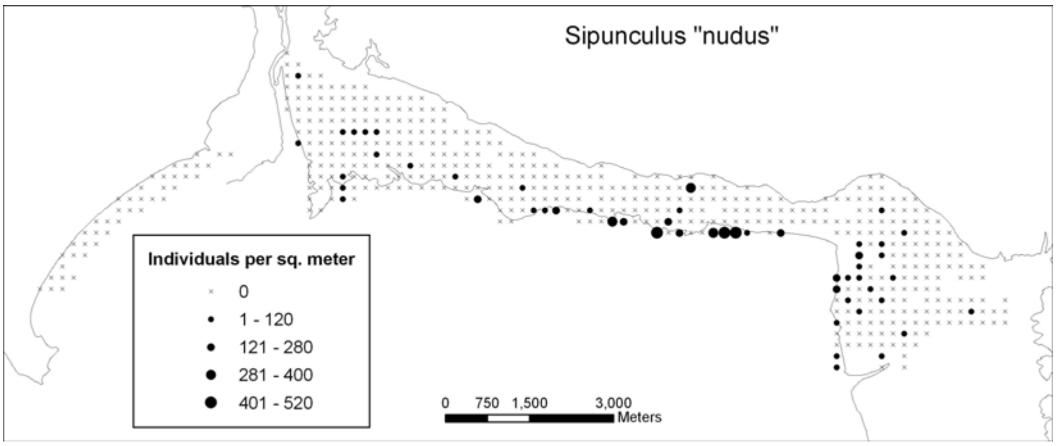


Fig. 30. Distribution of the peanut worms *Sipunculus* '*nudus*' across the northern intertidal flats of Roebuck Bay in June 2006 based on the core-sampling efforts.

Distributions of the near-vertebrates: dancing to the tunes of Tunicates

There is kind of a grey, phylogenetic, zone, resulting from the depths of time when the vertebrates found their origins in nearshore marine habitats. Species representing that grey zone are commonly found in the Roebuck Bay intertidal, and the most beguiling among then is a very primitive chordate, the lancelet fish *Amphioxis* sp. belonging to the species-poor class of Branchiostoma. The lancelet fishes of Roebuck Bay are a few cm in length; they are transparent small wriggly fishes without eyes, gills or jaws, that can bury themselves at great speed in the top layers of loose sediments. In June 2006 we found them along the northern shores, at all but one station, near the spring low-water mark (Fig. 31).

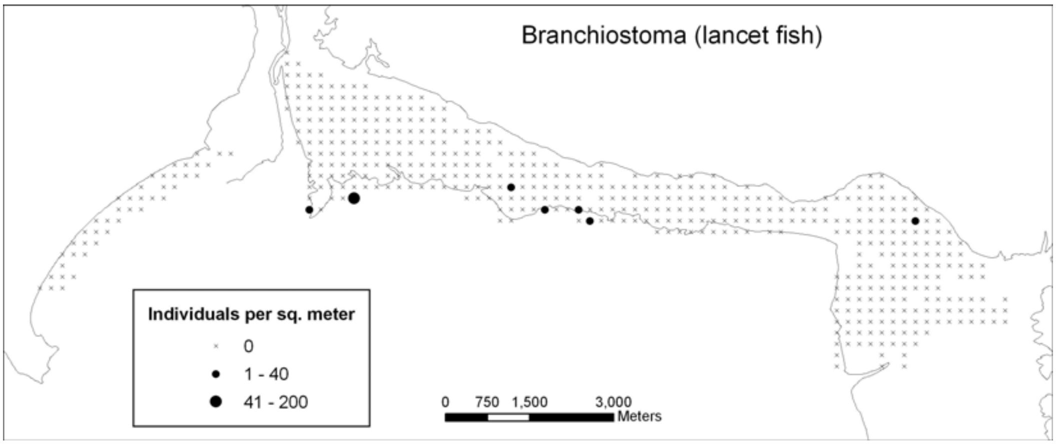


Fig. 31. Distribution of lancelet fishes (*Amphioxis* sp., Branchiostoma) across the northern intertidal flats of Roebuck Bay in June 2006 based on the core-sampling efforts.

In the case of lancelet fishes it is not hard to believe that these organisms are somehow ‘closely’ related to ‘us’ (the vertebrates), but this is not quite true for the sedentary ascidians, sea quirts or tunicates. In their larval phase they carry a notochord (precursor of the spinal chord) and for this reason share the phylum Chordata with lancelet fishes, fishes, amphibians, reptiles, birds and mammals. We all share the same ancestor with that rod-shaped extension of a frontal brain. Sea squirts or tunicates, after a free-living larval phase settle on a hard substrate on or in soft substrates. The tunicates growing on rocks often look like brightly coloured soft-skinned bagpipes, but the tunicates of soft intertidal shore are very indistinct. They are sand-coloured, and look like pretty lifeless sandy conglomerates (Photos 18). Indeed, their only signs of life are the puny little squirts of water that they eject when handled (hence the name sea squirt).

Tunicates have always been found on a few places in the intertidal, but in June 2006 they occurred in remarkable densities (Photos 18) over remarkable extends of intertidal habitat along the northern shores (Fig. 32). Probably four species occurred there: two or three solitary living species that were buried close to the sediment surface (one with a diameter of half a centimetre, another of 1-2 cm across and a third more uncommon form that was 4-5 cm across), sometimes occurring in carpet-like densities and always occurring in colonies (Photos 18). Then there was a rooted, colonial, form that also occurred in colonies but not over the same extent as the solitary species. Such large areas covered with tunicates were not found in previous surveys.

Photos 18. Overview (top) and detail (bottom) of the carpets of solitary tunicates on the lower intertidal flats along the northern shores of Roebuck Bay. Photos by Nicholas Branson.

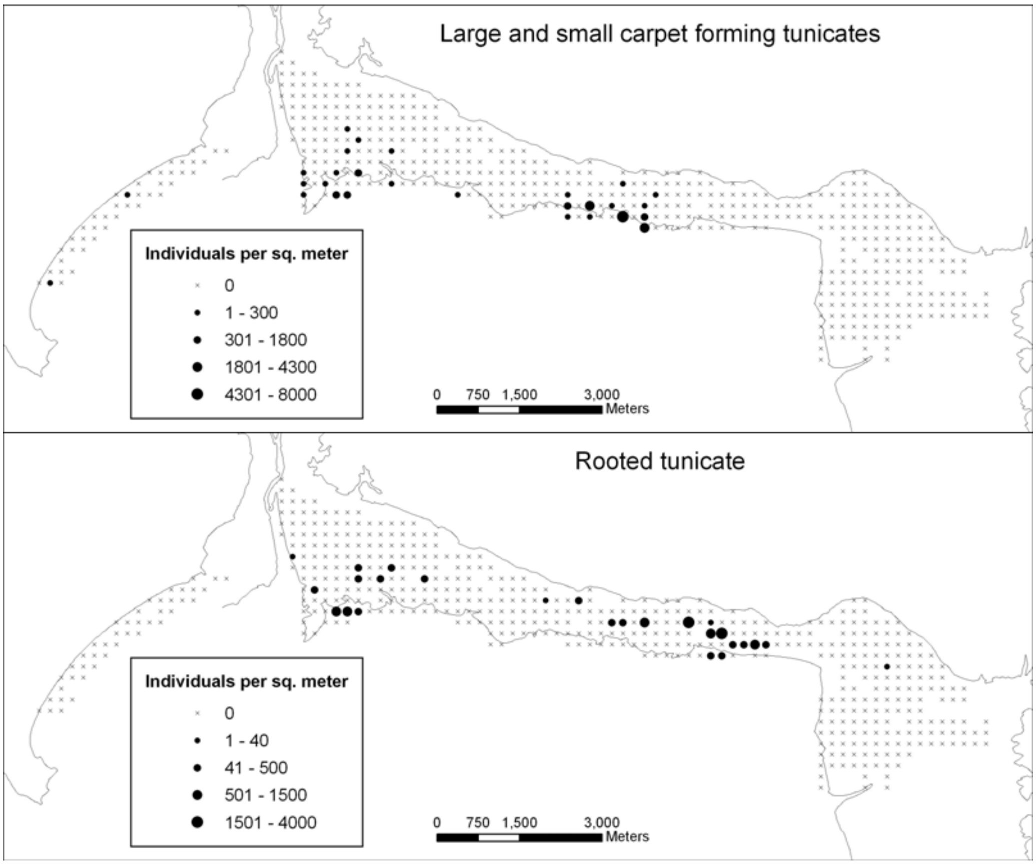


Fig. 31. Distribution of solitary tunicates of 2-3 kinds (top) and rooted, colonial tunicates (bottom) across the northern intertidal flats of Roebuck Bay in June 2006 based on the core-sampling efforts.

Photo 19. Preparation of the field sheets and labels by Anne Cloos (left) and Lucie Southern (right). Photo by Theunis Piersma.

Two trophic anecdotes: mollusc-eating starfish and crab-eating octopus

In the course of our walks on the mudflats, 'special events' occurred every so often. Here we report on two occasions where the type of predation, or the specific predatory event, surprised us. The first case is that of a seastar *Astropecten* sp. that we found on the intertidal flats of Town Beach in the morning of 30 June. The centre of its body was very bulgy; it was as if we could see and feel a bivalve inside. This seemed odd, as we believed that seastars would digest their food externally, rather than bringing it into their own body cavity. When we opened the *Astropecten*, however, we indeed found a fair sized venerid *Anomalocardia squamosa*, and a small moonsnail *Polinices*, inside the body (Photo 20). Note how large the bivalve is relative to the central cavity of the seastar. The observation implies that on the Roebuck Bay mudflats, seastars feed on molluscs and may therefore compete with molluscivore shorebirds, crabs and shovelnosed sharks. It also shows that they may ingest the entire prey inside the body before digestion, probably ejecting the emptied shells intact later on.

Photo 20. A seastar *Astropecten* sp. with a half ingested bivalve *Anomalocardia* and a moonsnail *Polinices* inside its body cavity. Photo by Jan Drent.

The second trophic surprise occurred half a day earlier, on the intertidal flats off Quarry Beach in the late afternoon of 29 June. Here, Helen Macarthur came across a large blue swimmer crab *Portunus pelagicus* that, when pulled out of the water, appeared to hold onto an other, smaller blue swimmer crab, but neither of those could be pulled out of the water to be examined because the smaller crab was held tight in the arms of a small octopus half buried under a rock. The octopus just continued to hold on after the big swimmer crab let go. Even after much pulling we could not free the swimmer from the octopus arms (Photo 21)! We concluded that blue swimmers can fall victim to even small octopus (rather than the other way around). In this particular case the big blue swimmer may have been attracted by the fight between small swimmer and octopus and then have opened competition with that octopus for a cannibalistic meal. It is a wild world out there on the mud!

Photo 21. Helen Macarthur pulling the leg of a blue swimmer crab *Portunus pelagicus* that is being held captive by a small octopus that has also clamped itself onto a rock. Photo by Theunis Piersma.

Shorebird distribution in the nonbreeding season

Overall we encountered 41 bird species on the intertidal flats, including 20 species of shorebirds. Non-shorebirds of interest included Sacred Kingfisher (generally considered a woodland bird, but we found 32 individuals standing on the mudflats, often over 1 km from the nearest vegetation), Silver Gull (694 mapped, a very high number for Roebuck Bay), and Whiskered Tern (910 seen – again a very high count by local standards, and uniquely, including some individuals which were running over the flats to catch crabs).

As we have found on previous surveys, different shorebird species had different feeding distributions on the mudflats. To a large extent this is likely to reflect spatial variation in prey abundance - most shorebird species are specialised to take different kinds of benthic prey – and in some cases it may also reflect preferences for a particular kind of substrate. Red-capped Plover, for example, was only found on firm sandy substrates west of Fall Point; this small, short-legged species hunts by chasing down small crabs, and cannot run fast enough to do so in deep mud. At the other extreme, the Black-tailed Godwit has a strong preference for soft sediments, and as was the case on previous surveys, we only found it feeding on the oozy muds at the mouth of Crab Creek.

Another species that has retained a consistent feeding distribution on the intertidal flats of Roebuck Bay is the Grey-tailed Tattler. As on previous expeditions, it was widespread on the western flats of the bay (Fig. 32), where it apparently hunts a wide range of surface-dwelling prey including small crabs and amphipods. In contrast, the feeding distribution of Great Knots and Red Knots has varied over the years. Both species are specialised to feed on bivalves, which are swallowed whole and must therefore be reasonably small; their preference for prey of this kind leads them to wander widely over mudflat systems, seeking recent spatfalls where suitably sized prey are available. Wherever they feed though, they show a preference for feeding sites near the sea-edge; recent (unpublished) work suggests that they follow the tide-edge closely in order to catch bivalves, which burrow more deeply after the tide has ebbed. In mid June 2006, Great Knots (Fig. 33) were found over a wide area of mudflats, albeit with the highest concentrations occurring in the east of the bay. In contrast, we could only find one feeding concentration of Red Knots (Fig. 34) – in the far east of the bay, just south of Crab Creek. This distribution of Red Knots came as a surprise to us, as the species tends to prefer slightly sandier sediments than Great Knot; however, the sediments where we found them concentrated south of Crab Creek in June 2006 are amongst the slushiest in the bay. It will be of interest to examine the benthos data for these sites to see if a particular benthic species had attracted them to this point.

In addition to the low tide surveys, we counted shorebirds at high tide, when they congregate on the roost sites along the northern beaches (Photo 22). In general, numbers of each species counted at these roosts corresponded very well with those counted at low tide ($r^2 = 0.928$, $n = 20$ species, $P<0.0001$), suggesting that we hadn’t missed any major feeding or roosting sites. In some species, such as Grey-tailed Tattlers, the roosting areas were close to the nearest feeding grounds (Fig. 32). In contrast, the feeding site for Red Knots was a good 5 km from the main roosting site found at Campsite Beach (Fig. 34).

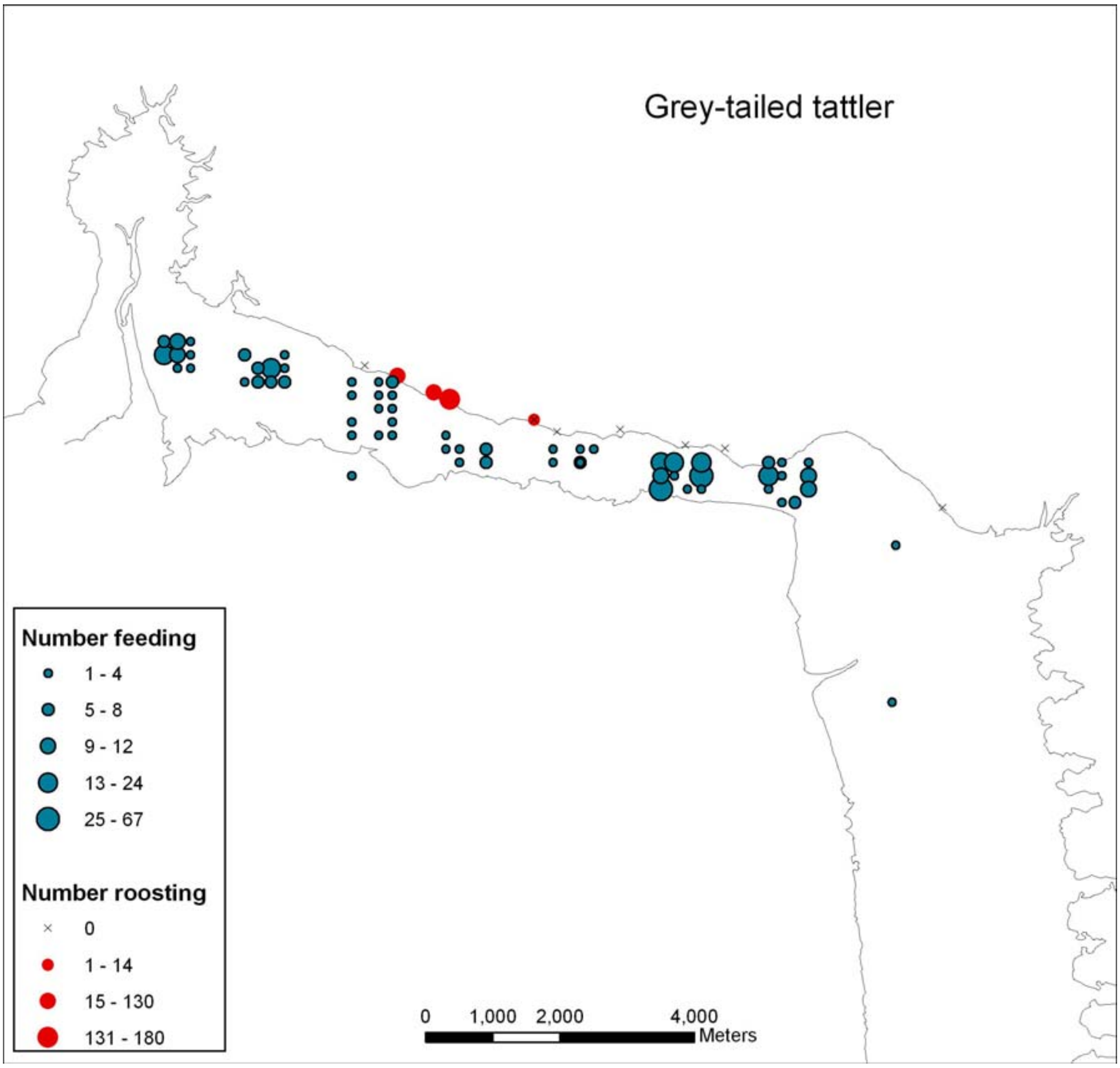


Fig. 32. Distribution of the high-tide roosts of Grey-tailed Tattler along the northern beaches of Roebuck Bay (red dots), and the distribution of Grey Tailed Tattlers over low-water intertidal bird-sampling areas (blue dots) in mid June 2006.

As has been the case on previous dry season surveys, we found relatively few shorebirds on the Dampier Creek Flats. Oddly though, our early impression is that benthos abundance on these flats was just as high as it has been on wet season surveys when this has been a favoured feeding region for shorebirds. It is possible that the cause of the discrepancy lies on high tide roosts rather than on the intertidal flats. The closest available roost sites to the Dampier Creek Flats, Quarry Beach and Simpson’s Beach, are both heavily disturbed in the dry season. Quarry Beach is used by moderate numbers of shorebirds nevertheless, but very high numbers of birds of prey and people leave Simpson’s Beach devoid of shorebirds at this time of year. For shorebirds that cannot tolerate the disturbance levels at these roost sites and therefore roost elsewhere, the costs of commuting to the Dampier Creek Flats to feed may be too high.

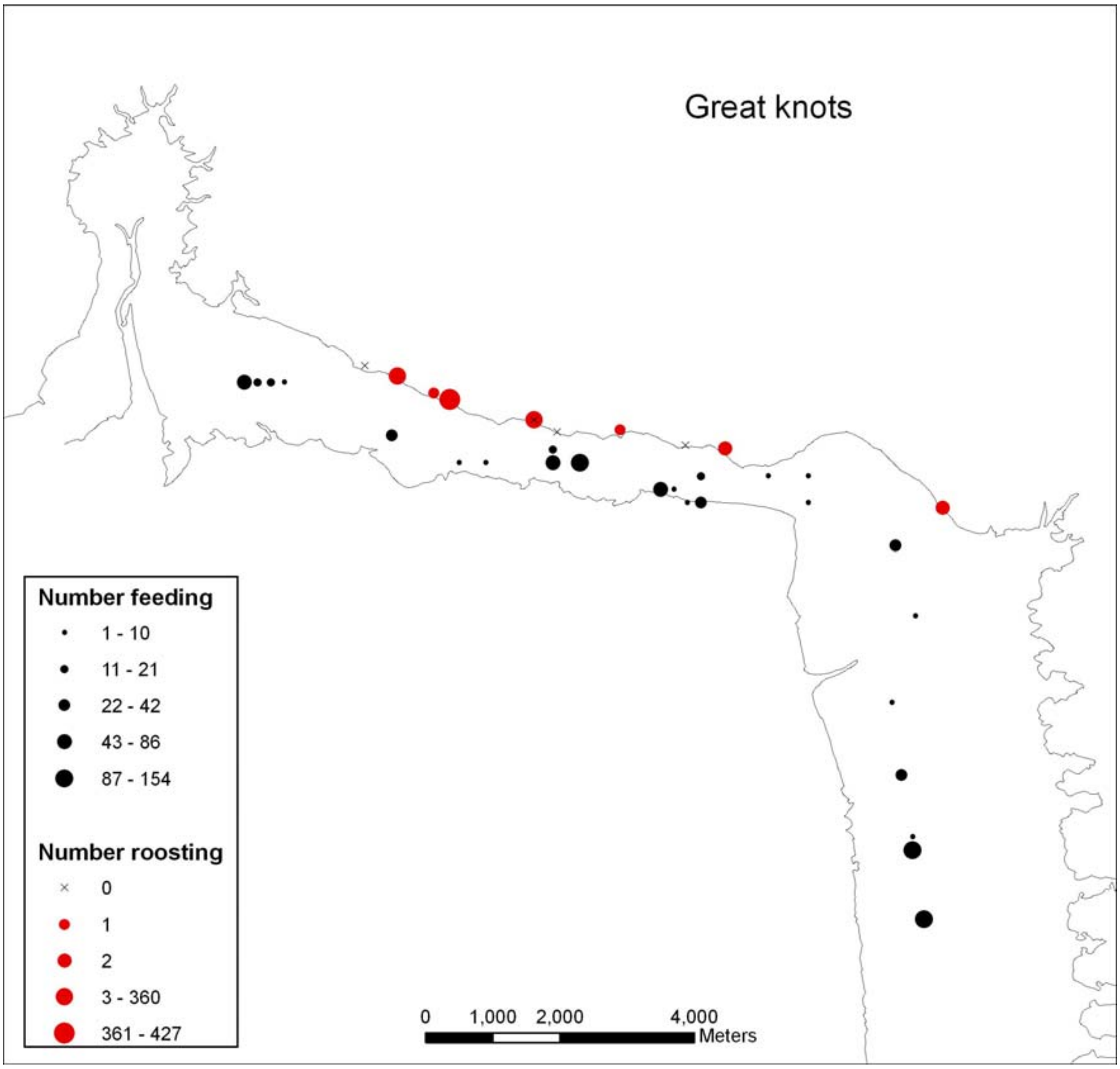


Fig. 33. Distribution of the high-tide roosts of Great Knots along the northern beaches of Roebuck Bay (red dots), and the distribution of Great Knots over low-water intertidal bird-sampling areas (blue dots) in mid June 2006.

Photo 22. Wader roost along the northern beaches at high tide. Photo by Eelke Folmer.

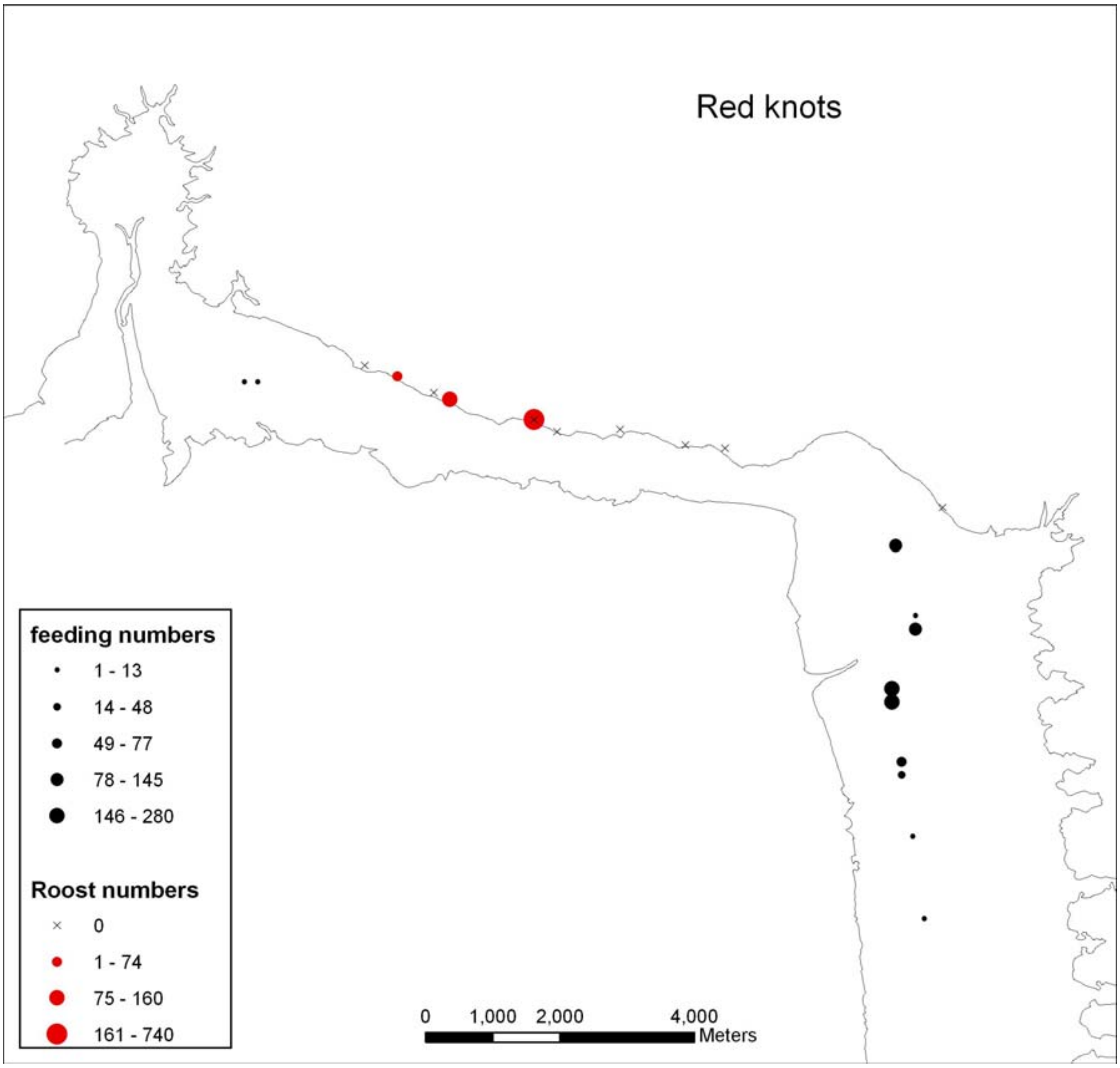


Fig. 34. Distribution of the high-tide roosts of Red Knots along the northern beaches of Roebuck Bay (red dots), and the distribution of Red Knots over low-water intertidal bird-sampling areas (blue dots) in mid June 2006.

5. General discussion: hotspots of benthic biodiversity

Wildlife managers as well as research ecologists are interested in measures that summarise patterns in species richness. Managers want such summary measures because it can help them to prioritise conservation or restoration actions. Ecologists are interested in such measures because it may help them untangling the complexities of food webs and community structure. ‘Biodiversity’ is a shorthand for the variety and abundance of organisms, and it can be expressed in several ways. Here we use the total number of species per sample and the commonly used Shannon-Wiener index to identify biodiversity hotspots. The Shannon-Wiener index is a measure that combines the total number of species and the evenness of the abundance of these species. We used the hotspot analysis tool from ArcMap 9.1 to identify spatial clusters of statistically significant high or low biodiversity. This tool calculates the Getis–Ord Gi* statistic. The G-statistic tells you whether high values or low values of biodiversity tend to cluster. We used a neighbourhood of 300 m that incorporates data from the nearest neighbouring sampling stations including the diagonal ones.

With all invertebrate species included (Table 2), it appeared that especially the Dampier Flats and the narrow intertidal zone just south of the Broome Bird Observatory were the richest in species numbers (Fig. 35). The same picture emerges when the Shannon-Wiener index is considered (Fig. 36), and both patterns are easiest seen after the statistical smoother routines of the hot and cold spot analyses (the bottom panels). That similar pictures emerge from the number of species and the Shannon-Wiener biodiversity index analyses is due to low numbers of individuals per species per sample. Nevertheless, it gives us confidence that we are working with robust measures of biodiversity. In the discussions that follow, for simplicity we will only consider the Shannon-Wiener biodiversity index.

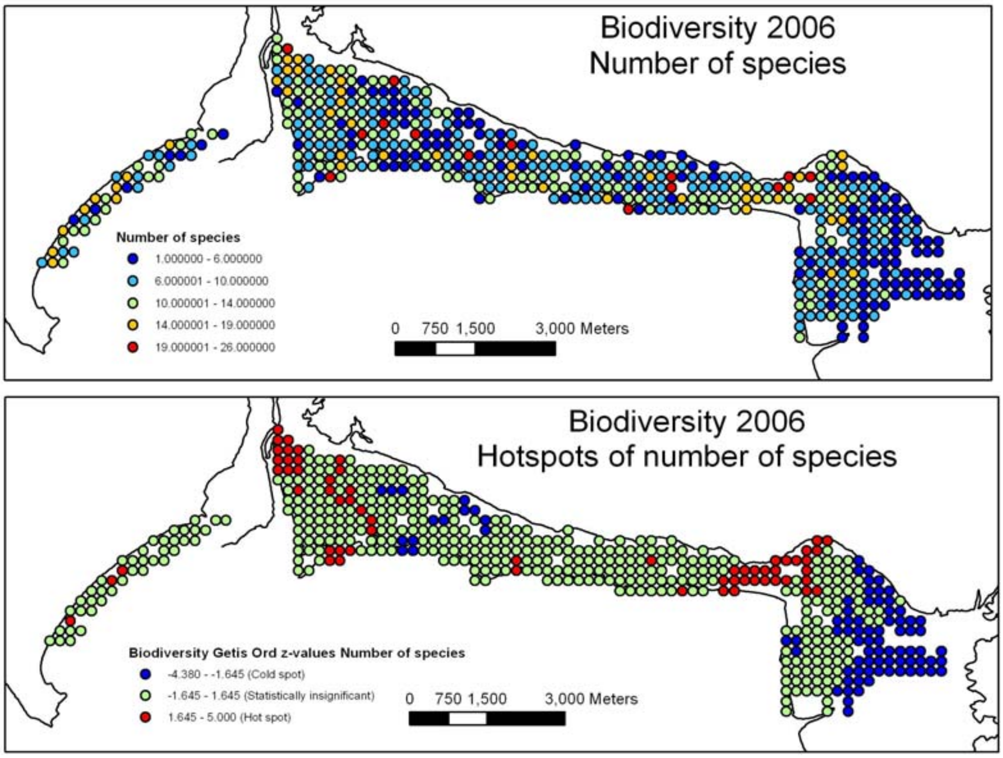
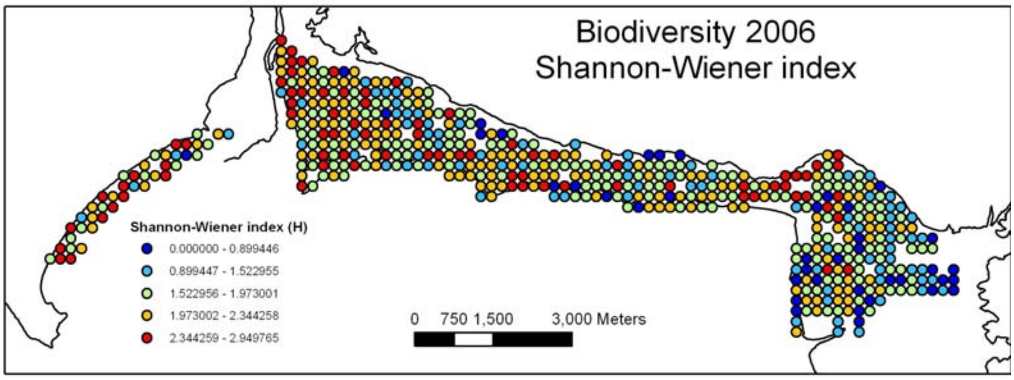


Fig. 35. The number of species per sampling position. Blue points denote species poor positions and successively richer towards red (top), and Biodiversity hot- and cold spots denoted by the Getis-Ord G*-statistic (bottom). Blue points show the statistically significant (5%) clusters of low diversity. Red points are the biodiversity hotspots at the 5% significance level. The neighbourhood consists of the neighbours that are within 300 m within each point.



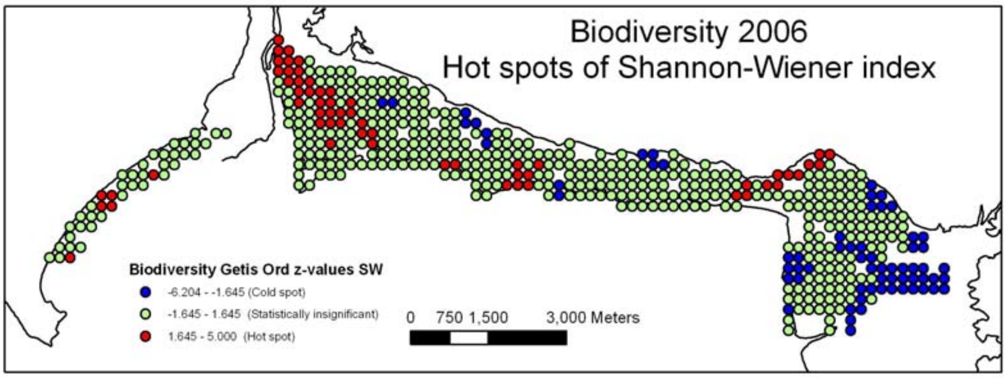


Fig. 36. The Shannon-Wiener biodiversity index per sample station. Red dots show the rich points and blue are the low biodiversity stations (top) and hot spots of Shannon-Wiener biodiversity (bottom). The red dots show clusters of statistically significant (at the 5% level) high biodiversity (hot spots) and the blue show clusters of significant low biodiversity (cold spots).

That the biodiversity hotspots are located just east of Dampier Creek and not very far to the north-west of Crab Creek, creeks being places with occasionally high run-offs of nutrients from the hinterland, invites speculation that nutrient inputs, at least in areas with threshold characteristics of the sediments, may result in locally high biodiversity. At this point it is impossible to say whether such suggestions are warranted, but future, more formal, analyses that are also based on the results of previous surveys and mapping data collected elsewhere in Northwest Australia (notably those from Eighty-mile Beach; Piersma *et al.* 2005) should help to verify thoughts such as these. However, the presence of bidioversity hotspots quite close to run-off points from the land do emphasise the long standing concerns about the likely detrimental effects of changes in water quality coming into the bay, e.g. as a result of the development of industrial (cotton) farming practices and other developments in the hinterland.

The largest cold spots appear in places with very soft oozy muds such as the area around Crab Creek (Fig. 36). This may have to do with the particular difficulties of living in soft muds, perhaps combined with the anoxic property of such silty environments. In fact, the correlation between penetrability (our measure of siltiness; see Fig. 5) and the G*-statistic of the Shannon-Wiener biodiversity shows a significant and negative value of -0.41 (Fig. 37 top).

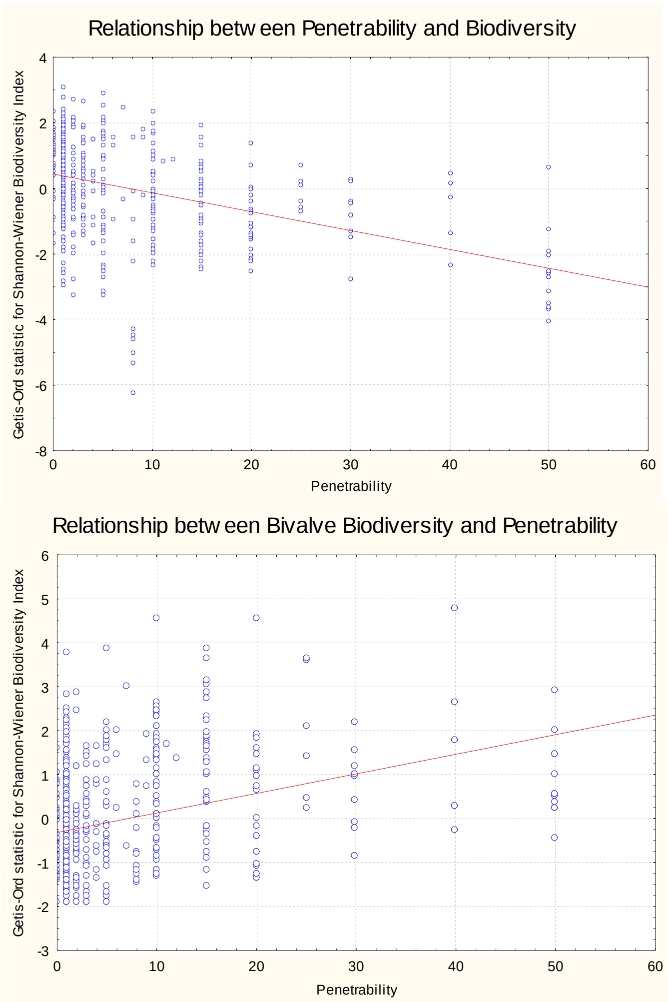


Fig. 37. The relationship between penetrability and biodiversity for all species (top; r = -0.41, p<0.05) and for the bivalves separately (bottom; r = 0.34, p<0.05B).

When the biodiversity of bivalves only is considered, the pattern is different enough to be interesting (Fig. 38). The biodiversity hotspots are still on Dampier Flats and near the Broome Bird Observatory. However, more careful investigation comparing Figures 36 and 38 shows that bivalve biodiversity hotspots are just next to the biodiversity hotspots of all species combined. In fact, the bivalve hotspots lie in much softer sediments than the overall hotspots. Whereas overall biodiversity was negatively associated with penetrability (Fig. 37 top), it turns out that there is a positive relationship between penetrability and bivalve biodiversity ($r = 0.34$, $p<0.05$) (Fig. 37 bottom)! That bivalves become more diverse in muddier sediments is consistent with the findings for Eighty-mile Beach, where Honkoop *et al*. (2006) documented negative relationships between number of bivalve species and overall bivalve densities per sampling station and the coarseness of the sediment (in this case properly measured as median grain size).

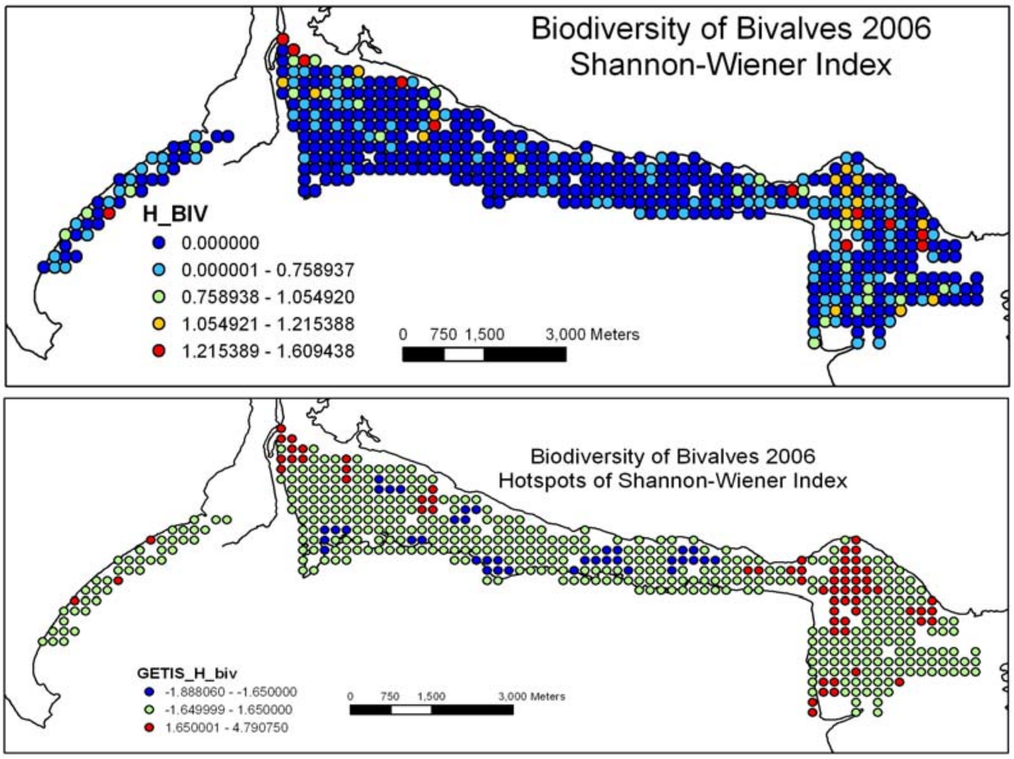


Fig. 38. Shannon-Wiener biodiversity index of bivalves (top), and hotspots of Shannon-Wiener bivalve biodiversity (bottom). The red dots show clusters of statistically significant (at the 5% level) high biodiversity (hot spots) and the blue show clusters of significant low biodiversity (cold spots).

All these results are clear-cut for the manager, and tantalising for the research ecologist and gives us a rich material for contemplation over the next few years. Note, however, that such hot and cold spot analyses inform us about macrozoobenthic biodiversity, not about the importance of different parts of the bay for birds. For example, red knots were found in greatest numbers around Crab Creek and south of it (see Fig. 34), areas which ended up as part of a biodiversity cold spot. Conservation importance has several different dimensions, the importance for predators such as birds being one, the representation of benthic biodiversity being another one.

6. Acknowledgements

A core group of 38 people participated in the field and laboratory work during ROEBIM-06: Nicholas Branson, Sally Burton, Anna Cloos, Jim Cocking, Peter Collins, Petra de Goeij, Sabine Dittmann, Justine Keuning, Agnes Cantin, Jan Drent, Eelke Folmer, Stephanie Gadal, Bob Hickey, Brad Wilson, Milo Wilson, Pieter Honkoop, Glyn Hughes, Brent Johnson, Ria Kitson, Loisette Marsh, Helen Macarthur, Kingsley Miller, Grant Morton, Maurice O'Connor, Grant Pearson, Theunis Piersma, Jack Robinson, Danny Rogers, Mavis Russell, Mike Scanlon, Holly Sitters, Lucie Southern, Ryan Vogwill, Doug Watkins, He Wenshan (Pearl), Bryan Webster, Kelly White and Kevin White.

This is the fourth "BIM" (Benthic Invertebrate Mapping project) on intertidal mudflats of the West Kimberley. The process of mapping the benthic organisms of the mudflats has now become so practised that the sampling sites for the whole of the northern side of the bay plus parts of the western shores, were mapped in record time.

Funding for this project was provided by a number of agencies: CALM Science Division, CALM West Kimberley District, CALM Landscope Expeditions, Central Washington University, Flinders University, Schure Beijerinck-Popping Fonds and Netherlands Organization for Scientific Research (NWO).

We acknowledge the Aboriginal cultural and heritage importance of the Bay and thank Micklo and Nyaparu for their interaction following the Celebrate the Bay Day and general support for our work. We also thank and acknowledge the role played by Environs Kimberley in the promotion of and support for our field survey. We were particularly grateful for the welcome extended by Rubibi at the community Celebrate the Bay forum.

The Broome Bird Observatory provided a wonderful venue and facility for the benthic surveys and we received great hospitality from wardens Pete Collins and Holly Sitters and the BBO Committee. The value of the BBO mudlab was again demonstrated as sorters and identifiers worked into the nights to complete their tasks. Thanks also to Lloyd, Peter, Naoko, Jeff and Joan for their cheerful assistance. Special thanks to Chef Maurice O'Connor for his inspirational cooking and kitchen organisation and, of course, thanks to his willing roster of helpers who ensured we had quality meals at all times.

We thank and acknowledge Landscope Expedition members Nicholas Branson and Ria Kitson for their financial contributions and for their spirited, enthusiastic participation in all aspects of the project. Jim Cocking, Brent Johnson and Mike Scanlon provided exceptional logistical support for the project, during the early preparations and throughout the survey. Their willingness to work beyond the call of duty and their whole-hearted approach to their work ensured the success of the project. CALM's Perth District provided a very useful 3 person hovercraft for the duration of the expedition and Glyn Hughes again demonstrated exceptional skill and endurance during the survey. (See Table 3 and photo below).

We also thank Anne Cloos from Luxembourg and Jack Robinson from Sydney for their great effort in the preparation of the field equipment for each sortie to the mudflats: we gratefully presented them the joint 2006 *BIMbo* awards (*B*enthic *I*nvertebrate *M*apping *b*ucket *o*rganiser in recognition of their fine efforts) Thanks to Lucie Southern and Stephanie Gadal (CALM volunteers) for their high level of support throughout the survey. Loisette Marsh continued to provide superlative and essential support for identification of a number of groups of invertebrates, particularly the echinoderms.

We were especially grateful for the input from Broome locals Helen Macarthur, Kingsley Miller (CALM, West Kimberley District Wildlife Officer), Bryan Webster (Paspaley Pearls) and Sally Burton. Brad Wilson from Central Washington University provided great support in the field and in the lab. Milo Wilson, who accompanied his son Brad from Yakima, USA, was a great source of` enthusiasm. His resourcefulness extended to running repairs on hovercraft, vehicles and equipment. Kelly and Kevin White joined us fresh from the South Korean

intertidal mudflats of Saemangeum and were a welcome inclusion into our teams.
We were fortunate to be joined by Dr He Wenshan (Pearl) from East China Normal University. There are strong possibilities for continued interaction between us on benthic research.

Doug Watkins (Wetlands International), Helen Macarthur and Mavis Russell assisted with the data entry. Helen continued to provide enormous amounts of cake and biscuits that kept the expedition energy levels at an all time high. In the aftermath at BBO, keen visitor Michael Gallagher helpfully proof-read the draft report and made many helpful and encouraging suggestions.

Table 3. Distribution of the 26 hours in the field by the CALM hovercraft operated by Glyn Hughes.

Goal	Date	Operational time (hrs)	Time	Accompanying persons
Benthos	13 June	3	0600-0900	Jack& Lucy
Benthos	14 June	4	1500-1900	Jack & Brad
Benthos	15 June	4	1600-2000	Jim
Benthos	16 June	3.5	1530-1900	Nicholas
Benthos	18 June	4	0700-1100	Nicholas & Kevin
Benthos	19 June	4	0730-1130	Kelly & Mike
Birds	20 June	3.5	0830-1200	Danny & Theunis

The bird team gearing up one of the two hovercraft on 20 June. Photo by Grant Pearson.

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Appendix: **Diary of events of ROEBIM-06**

As recalled by Stephanie Gadal, with assistance from Lucie Southern and Anne Cloos

8 June 2006
The road team met at Woodvale, finished off packing the trailers and getting the gear organised and we headed off… We left around 10 am and drove and drove and drove! After a few stops and really bad meals at roadhouses we finally reached Meekatharra and turned into the bush to set up our swags and have a good night's sleep. It was so cold!!! Slept with a sleeping bag, a doona and a swag but our noses were still cold. Still, it was awesome to fall asleep watching the stars.

9 June
Got up with the sunrise, I watched it from inside my swag. Had a quick breakie and we were off again. We drove through the Pilbara, the oldest piece of land on Earth, it was very beautiful. We saw a dingo, that was cool! We didn't find a good piece of bush so we just camped on a small road. We were promised warmth but it was still very cold.

10 June
After the final 5 hours of the trip, we arrived in Broome and stopped in town for a proper coffee. We had been travelling for 30 hours, 2400 kms to get to our research site. We are camping at the Broome Bird Observatory (BBO). The camp is very civilised: hot showers, indoor kitchen and we've got our own cook! Met some more members of the team, we expect a total of 35 people from many different nationalities.

11 June
This morning, we unpacked all the gear and set up the lab. After getting organised, part of the team went for a swim on Cable Beach and we all came out of the water with a rash (maybe stingers). We arrived back at camp for dinner cooked by Maurice (our chef) and Grant went to pick up the Dutchies at the Broome airport. They arrived very tired and went straight to bed, we sat around the fire for a while.

12 June
In the morning, we were assigned different jobs, Jack and Anne will be in charge of bucket organising for the trip. We had lunch, followed by a training sampling run on the beach. We got our first experience on the mudflats, walking can be quite a challenge! Saw lots of crabs and we found a dead stingray on the beach and after taking lots of pictures we removed the sting and took it back to camp. At sunset the colours were incredible with the red cliffs, brown mud flats and turquoise waters. After returning and a nice dinner, the rest of the evening was spent sorting through samples. We finished our day by watching the Soccer World Cup at the warden's house, Australia beat Japan 3 to 1!!!

13 June
I spent some of the morning sorting and the rest helping Maurice as I was on kitchen duty with Jim. In the arvo, we headed out to the flats. After recovering from a slight scare from a shark sighting (it was only 50 cms long but still scary), we carried on our duty as volunteer samplers and sorters until 10pm.

14 June
Had the worst night of my life, spent it throwing up! I had to get out of my sleeping bag, get

out of my tent, face the freezing cold, find a bush in the dark and… Lucie came to tell me that 7 other people were sick like me all night. We have reached the conclusion that we are all infected with a very contagious virus called Nora virus. The source appears to be Grant, thanks a lot! We were all put in a chalet, in isolation for 24 hours and I listened to a lovely chorus of sick people all day long. The healthy part of the team (though they kept dropping like flies, 10 sick by the arvo) went out on the mudflats and stayed sampling until after sunset. I went for a short walk in the evening to watch the staircase to the moon on the mudflats, it was very spectacular.

The wonderful sunset over the mudflats on 15 June (photo by Stephanie Gadal)

15 June
I woke up feeling much better, which was nice, it being my 24th birthday! The morning was spent sorting through samples and at lunch we had a birthday cake for myself and Theunis' birthday. Lucie took the time to make them but only the brave ate them after we blew out the candles and spread our Nora virus germs! We headed out to the mudflats in the afternoon to work until after sunset. I can honestly say that it was one of the most amazing experiences of my life. The sun came down and set and all the mudflats turned pink and red. Then it slowly got darker and the stars were surrounding us. The bioluminescent ostracods lighting up our footsteps were one of the highlights of the night. We also saw an octopus, a turtle, rays and many different types of coral. I felt very privileged to have the opportunity to witness life on the mud at night. But wonder turned to tragedy… Back at camp, after an unfortunate encounter with the stingray barb, Jan was rushed to hospital with the barb still protruding from his hand and the threat of amputation always on his mind. With a great sense of timing, Lucie, suffering from severe abdominal pains, kept Jan company in the "Budget" ambulance. Grant (the driver) comforted Lucie by advising her that very few people die between the BBO and the Broome hospital. I can't print Lucie's reply… On arrival at the hospital, there was some delay at gaining entry through the emergency ward. After Lucie threatened to vomit on the doorstep, entry was finally gained when Jan picked the lock with the blunt end of the stingray sting. The nurse, who held a strong resemblance to Frankenfurter from the Rocky horror show, offered Lucie drugs and a threadbare blanket and successfully removed the stingray sting after Jan was asked to pose for a number of photographs by the head surgeon. We finally returned to camp to a cold dinner and a well deserved birthday drink and a share of

Lucie's Valium! Once the Valium had taken effect and Grant was relaxed, he suddenly realised that he had left his boss stranded at the airport! What a day!

Stung by the barb of a dead stingray! (photo courtesy Jan Drent)

16 June
The morning was spent sorting through many samples. In the arvo, I was lucky enough to go sampling on the "hoovercraft" . It was an amazing sensation to be gliding on the mudflats and we were surrounded by 100s of waders. The reason we sample with the hovercraft is that the mud is too deep to walk in, so getting out of the boat to sample was a real challenge! A beautiful sunset over the mudflats was a perfect end to a perfect day.

17 June
No sampling or sorting today but still a very busy day. We all went to the "Celebrate the Bay Day" at CALM in Broome. The forum was attended by many locals keen to learn more about the Bay and we were provided with a range of presentations about the ecology of the Bay. After a nice seafood barbie, we headed out to Minyirr Park to learn more about the Aboriginal culture and history in the region. The whole team then met up at the Mangrove Hotel for food and drinks.

18 June
A very relaxing day (but it is Sunday), sorting samples, helping in the kitchen and a barbie in the evening. Back to sampling tomorrow.

19 June
We went out sampling this morning at Town Beach and we had a brush with death as a sea snake leapt past our bare legs! After an arvo of sorting we had a gathering with the team and an educational talk about bivalves. Tomorrow we are facing the challenge, sampling in mud of a penetrability index of 10 (deep, deep, deep and meaningful mud)!

20 June
Today, the team regressed to childhood. Good and professional intentions rapidly degenerated into one mad mud fight. It all started with the ever sensible Grant throwing mud at my face, followed by a swift rugby tackle by Petra and war began… An hour later the team emerged from the primordial slime, exhausted and covered from head to toe in mud. Lucie even had a mudskipper land on her arm and get confused! Getting hosed down was not so much fun but we now have soft hair and skin! This evening was spent winding up with the Science results and a slide show of activities and events of the expedition. Tomorrow, the team from Perth returns by road leaving behind great friends and very fond memories…

Group photo ROEBIM-06:

From left to right: Bryan Webster, Grant Pearson, Jan Drent, Jack Robinson, Maurice O'Connor, Helen Macarthur, Jim Cocking, Bob Hickey, Petra de Goeij, Mavis Russell, Pieter Honkoop, Ria Kitson, Loisette Marsh, Glyn Hughes, Mike Scanlon, Theunis Piersma, Agnes Cantin, Danny Rogers, Milo Wilson (squatting), Anne Cloos, Eelke Folmer, Stephanie Gadal, Justine Keuning, Nicholas Branson, Lucie Southern, Brad Wilson (squatting), Kevin White, Kelly White, He Wenshan (Pearl), Brent Johnson, Sabine Dittmann (squatting), and Sally Burton.

Appendix 2:A SUMMARY OF OUTPUT FROM BIRD AND BENTHOS WORK -1996 to 2006

The following refereed and unrefereed journal publications have resulted from the bird & benthos work (with CALM/NIOZ involvement) since 1996:

Battley, P. F., Piersma, T., Dietz, M. W., Tang, S., Dekinga, A. and Hulsman, K. 1999. Differential organ reduction during bird migration. Stilt 35: 60.

Battley, P. F., Piersma, T., Dietz, M. W., Tang, S., Dekinga, A. and Hulsman, K. 2000. Empirical evidence for differential organ reductions during trans-oceanic bird flight. Proceedings of the Royal Society of London B 267: 191-196.

Battley, P. F., Dekinga, A., Dietz, M. W., Piersma, T., Tang, S. and Hulsman, K. 2001. Basal metabolic rate declines during long-distance migratory flight in Great Knots. Condor 103: 838-845.

Battley, P. F., Dietz, M. W., Piersma, T., Dekinga, A., Tang, S. and Hulsman, K. 2001. Is long-distance bird flight equivalent to a high-energy fast? Body composition changes in freely migrating and captive fasting great knots. Physiological and Biochemical Zoology 74: 435-449.

Battley, P. F., Rogers, D. I., Piersma, T. and Koolhaas, A. 2003. Behavioural evidence for heat-load problems in Great Knots in tropical Australia fuelling for long-distance flight. Emu 103: 97-103.

Battley, P. F., Rogers, D. I. and Piersma, T. 2003. Late migratory departures of red knots (*Calidris canutus*) from north-west Australia. Notornis 50: 180-181.

Battley, P. F., Piersma, T., Dekinga, A., Rogers, D. I., Spaans, B. and van Gils, J. A. 2004. Do body composition and plumage during fuelling predict northward departure dates of Great Knots (*Calidris tenuirostris*) from north-west Australia? Ibis 146: 46-60.

Battley, P. F., Rogers, D. I., van Gils, J. A., Piersma, T., Hassell, C. J., Boyle, A. and Hong-Yan, Y. 2005. How do red knots *Calidris canutus* leave Northwest Australia in May and reach the breeding grounds in June? Predictions of stopover times, fuelling rates and prey quality in the Yellow Sea. Journal of Avian Biology 36: 494-500.

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